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ABSTRACT

REMOTE MEASUREMENT CALIBRATION IN POWER SYSTEM

by
Xiaofeng Li

Power system reliability and economy of operation require accurate measurements of current, voltage, real and reactive powers. These measurements are transmitted to a control center of a power system for monitoring, display, and use in power system real-time analysis. The number of measurements is in thousands. Routinely field technicians must calibrate transducers and/or determine other sources of metering errors. Due to the large number of measurements and the time required to check each individual measurement, field calibration procedures are impractical, expensive, and not timely.

There has been a need for a more efficient approach to measurement calibration and identification of defective instruments. This paper describes an approach which meets the need. The collection of measurements over time are used to correct for systematic errors, (caused by instrument transformers, transducers, secondary leads between these devices, analog-digital converters, and the scaling procedure). The volts, watts, and vars scales are then adjusted to compensate for these errors, thus providing more accurate measurements.

REMOTE MEASUREMENT CALIBRATION IN POWER SYSTEM

by
Xiaofeng Li

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Electrical Engineering

Department of Electrical and Computer Engineering

May 1996

APPROVAL PAGE

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This thesis is dedicated to
my wife Hong Li, and my new-born daughter Christine Li .

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CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this thesis is to propose a method to make up for the measurement errors and provide scale adjustments, that is, remotely calibrate real and reactive power and voltage measurements. This approach requires information concerning the network configuration, the impedance of all transmission lines, and *reliable data* measurements at a few points of the system. The proposed algorithm consists of determining calibration coefficients for the various measured values by using alternately *bus power balance* and *current equality or line power loss,* starting from reliable points and propagating the process throughout the network. Finally the measurements are calibrated by means of those calibration coefficients for all hours at which they were taken.

1.2 Background Information

Today, Energy Management System (EMS) plays an important role in power system operation and analysis. It contains Supervisory Control and Data Acquisition (SCADA), Automatic Generation Control/Economic Dispatching Control (AGC/EDC), State Estimation (SE), Power-Flow, Contingency-Analysis, Transients Analysis, Generation Schedule/Unit Commitment etc. application programs. Typically, SCADA collects the measurement (P, Q, V) from Remote Telemetering Units (RTUs)s located in substations and power plants of a power system. State Estimation retrieves the measurement data from SCADA application and then suppresses the gross and spurious errors , furnishing dependable real-time database for other advanced analysis applications. An overview of an EMS is illustrated in Figure 1.

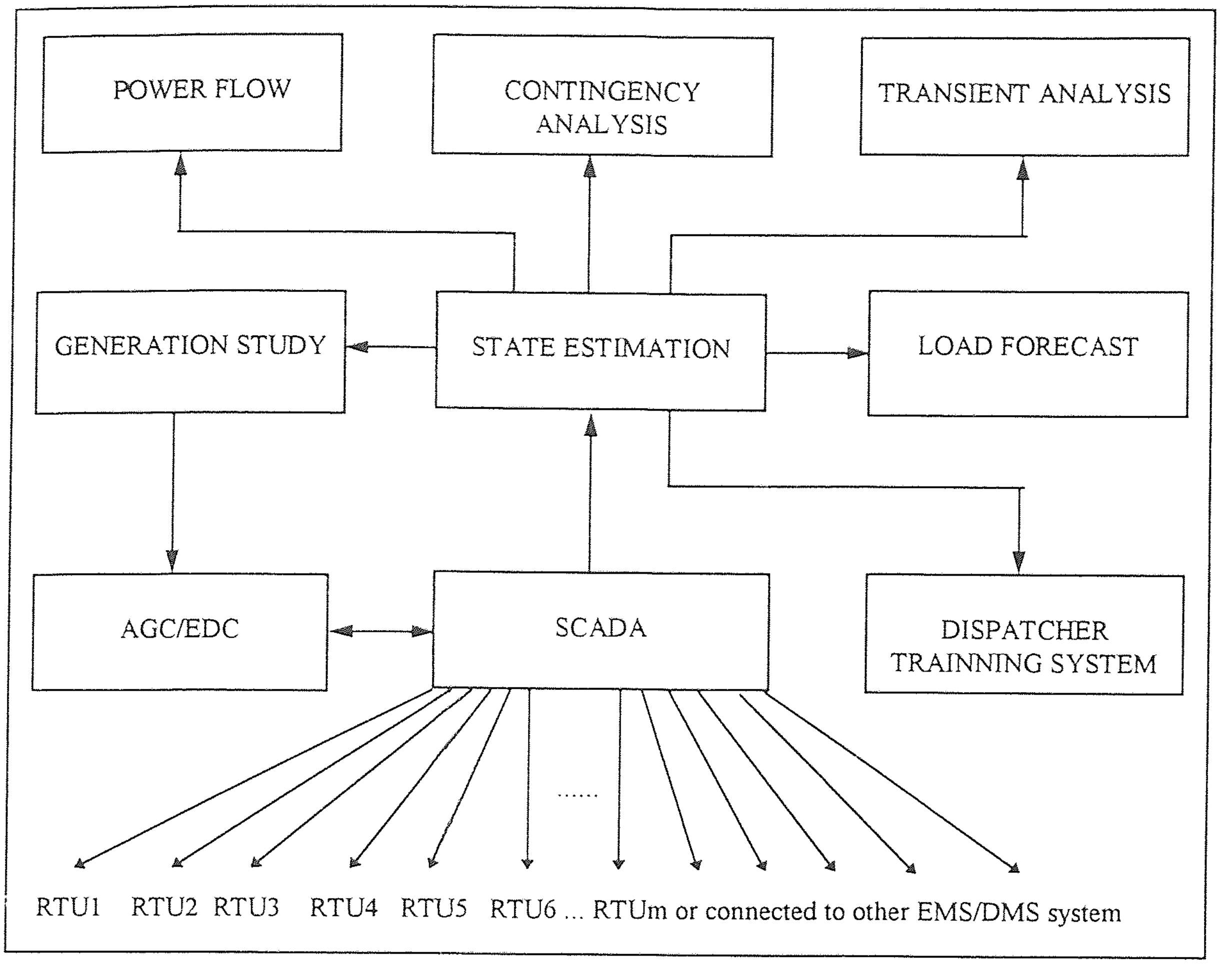


Figure 1 EMS OVERVIEW

Accuracy in this case means that data be free of systematic errors because the state estimator assumes that the data are unbiased and are only subject to random errors of known mean and standard deviation. Only spurious errors are detected by SE.

Error analysis is described in many paper [1], [2]. Errors in measurements are broadly categorized as systematic errors and random errors. Systematic errors are those resulting from malfunctions and adjustments which may conceivably be easily corrected when detected, the only impediment to detection being cost. Each measurement received is the final product of a chain of instruments and processes. The chain consists of instrument transformers, transducers, and analog-to-digital converters linked together with "secondary" wiring at the substation; scaling and conversion procedures at the control center (performed by SCADA of EMS); and telemetering gear and communication equipment in between . These devices, linkages, equipment and procedures all, to a different degree, introduce errors in the measurement streams. The instruments drift and deteriorate with time, temperature and environmental conditions requiring periodic inspection and calibration. Hence, all of the above factors generate errors that may be classified as systematic errors. The measuring processes and devices are shown in Fig.2 .

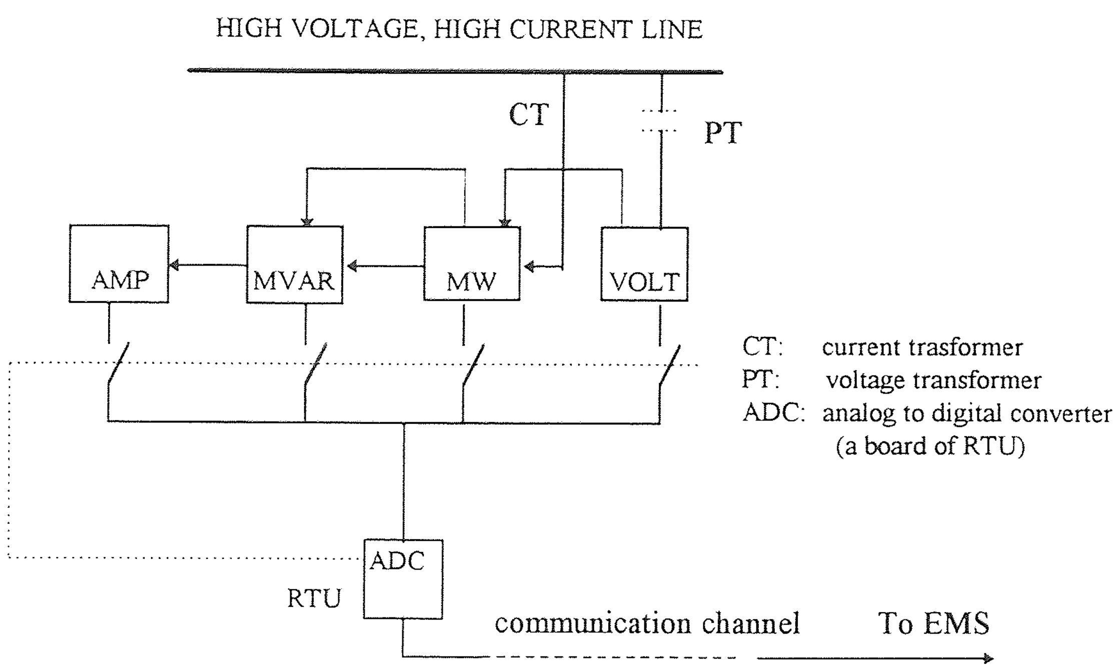


Figure 2 The Processes of Data Acquisition

Random errors are those that are unknown and impossible to rectify by means of service adjustments. While systematic errors can be reduced by a well-administered maintenance plan of field calibration, economy of operation sets a limit on the extent of such a plan, thus precluding perfect calibration at all times, no matter how well intended and designed the plan is. The techniques presented in this paper have for goal to process the measurements in order to minimize the systematic errors, in essence performing remotely the *soft calibration* of the measurements. This would certainly improve the performance of the state estimator.

The study of remote measurement calibration (RMC) is of interest. Many studies were published in the last ten years. The work of Adibi et al [5] presented the calibration as a correction based on measurements of bus voltage magnitude and phase angle, in addition to line real power and reactive power flows. This was an improvement over the earlier works by Adibi et al [3], [4], phase angle measurement was dispensed with. It uses bus summing for real and reactive power and KV equality at each bus. A nonlinear relationship was used between measured and calibrated values, including zero offset and gain adjustment.

E. Cohen and A. Fallaha [6] proposed a method, which is a mix of physical and soft calibration. It requires the selection of a few reliable points for regular, frequent field calibration. The reliable points give a power reference to the system. Power balance, power loss and voltage drop constraints are used to minimize softly the systematic errors.

CHAPTER 2

METHOD OF CALIBRATION

The algorithm presented in the sequel for remote measurement calibration (RMC) requires reliable data measurement at a few points of the power system. This means that at those points field calibration and data transmission have to be checked much more frequently than what is considered routine for the rest of the system. The selection of the point locations depends on the system configuration and their number on the minimum that is found to produce acceptable results. The planner should then experiment, using the algorithm, with different sets of reliable points in order to arrive at what he considers to be adequate set of reliable measurement points. The calibration at those points is then assumed to be perfect and in no need for correction. Measurements at those points are only subject to random errors. Using the measurements at the reliable points, the algorithm proceeds to calibrate the measurements at the other points of the system. The reliable points, therefore, serve as a reference for the power and voltage levels of the system without which no correction is possible. Indeed, reducing all measurements to nil satisfies perfectly all laws of conservation of energy.

2.1 Mathematical Model

The linear model describing the relationship between the corrected and measured values of P, Q, and V can be written as follows:

$$V_{c\,jh} = a_{1j} + b_{1j} V_{mjh} \tag{1}$$

$$P_{cih} = a_{2j} + b_{2j} P_{mjh} \tag{2}$$

$$Q_{cjh} = a_{3j} + b_{3j} Q_{mjh} \tag{3}$$

where:

subscript c stands for calibrated

subscript m stands for measured

subscript j refers to a particular bus number

subscript h refers to a particular hour of the day

V_{cjh} : the calibrated value of voltage at hour h for point j.

P_{cjh} : the calibrated value of real power at hour h for point j.

Q_{cjh} : the calibrated value of reactive power at hour h for point j.

V_{mjh} , P_{mjh} , Q_{mjh} are the measured values at the point j and hour h.

a_{1j} . a_{2j}, a_{3j} and b_{1j} , b_{2j} , b_{3j} are the zero offsets and the gain coefficients for point j, respectively .

Now, a relationship must be found among calibrated values, measured values and network elements, and establish equality constraints. When the measurement data violate these constraints and introduce systematic errors, Nonlinear Least-Square techniques are used to minimize these errors.

$$\min \sum_{h=1}^{H} \left[\sum_{i=1}^{N} F_{ih}(X)^2 \right] \tag{4}$$

where H is the number of hourly measurements.

N is the number of equality constraint functions.

$F_{ih}(x)$ is the i-th component of the constraining function at hour h.

Broadly speaking, the constraint function (or objective function) involves violations to conservation of energy that must be minimized. The result must satisfy the reliable values assumed at some points and not be trivially zero. The reliable points have therefore the effect of setting the level at which conversation of energy is to be satisfied. It is worth noting that from a practical point of view P and Q are commonly measured in contrast to phase measurements or even current measurements.

The following simple case is used to illustrate the calibration procedure. In Figure 3, a system has seven measuring points 1, 2, 3, 4 at bus I and 5, 6, 7 at bus J. we assume point 1 and 2 are reliable measurement.

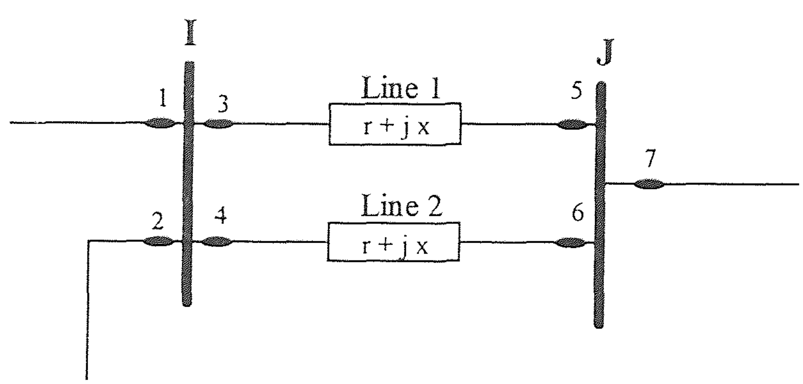


Figure 3 One Line Diagram of a Simple System

2.1.1 Power Balance Constraint

The objective function adopted here is the squares of the power summation at one bus over time, plus the sum over time of the squares of the difference between the calibrated and measured value. This objective function ensures that the calibrated values stay close to the measured values refer to a certain power level by the reliable points at this bus. We explain this by Figure 3, a simple example.

$$P_{c1} + P_{c2} + P_{c3} + P_{c4} = 0 \tag{5}$$

$$Q_{c1} + Q_{c2} + Q_{c3} + Q_{c4} = 0 \tag{6}$$

Where P and Q are taken positively if entering the bus and negatively if leaving it. The vanishing summations are hardly possible. Hence, we can rewrite the above equations in coefficients form as follows:

$$P_{c1} + P_{c2} + a_{23} + b_{23}P_{m3} + a_{24} + b_{24}P_{m4} = \varepsilon_{pI} \tag{7}$$

$$Q_{c1} + Q_{c2} + a_{33} + b_{33}Q_{m3} + a_{34} + b_{34}Q_{m4} = \varepsilon_{qI} \tag{8}$$

In general form:

$$\sum_{j=1}^{R} P_{cj} + \sum_{j=R+1}^{M} \left(a_{2j} + b_{2j}P_{mj}\right) = \varepsilon_{pI} \tag{9}$$

$$\sum_{j=1}^{R} Q_{cj} + \sum_{j=R+1}^{M} \left(a_{3j} + b_{3j}Q_{mj}\right) = \varepsilon_{pI} \tag{10}$$

R is the number of reliable points at bus I.

M is the total number of measured points at bus I.

ε_{pI}, ε_{qI} are the error resulting from the mismatches of the corrected powers at bus I.

The second power constraint will be the difference between measured and corrected values for each measured point. Its purpose is not to allow the calibrated value to stray too far from the measured value. Equation (9) may be minimized , for instance, by having $a_{2j}=b_{2j}=0$ for some j ; this is unacceptable. In addition, then at bus I, we have :

$$P_{mj} - a_{2j} - b_{2j}P_{mj} = \varepsilon_{pj} \qquad \text{j=R+1, M} \tag{11}$$

The errors for real power at bus I in the Figure 3, using the power balance constraint, are then ε_{pI} , ε_{p3}, ε_{p4} . The power balance objective function to be minimized involves the power balance constraints described above for all hours of the period of measurements. The total number of measurements is equal to M×H over that period. The objective function at bus I can be written as follows:

$$\min\left(\sum_{h=1}^{H}\varepsilon^2_{pIh} + \sum_{h=1}^{H}\sum_{j=R+1}^{M}\varepsilon^2_{pjh}\right) \tag{12}$$

Same reason, we can write the objective function of reactive power at bus I :

$$\min\left(\sum_{h=1}^{H}\varepsilon^2_{qIh} + \sum_{h=1}^{H}\sum_{j=R+1}^{M}\varepsilon^2_{qjh}\right) \tag{13}$$

Let us just take H hours of measurements , assume F be the error squared forming the objective function and F_p that corresponding to real power (P). For the sake of clarity, a and b are ow used as the offset and gain of real power , not a2 and b2 , because real power is used to explain the procedures. This obviates confusion with other subscripts. The complete expression follows :

$$F_p = \sum_{h=1}^{H} \left[\left(P_{c1h} + P_{c2h} + a_3 + b_3 P_{m3h} + a_4 + b_4 P_{m4h}\right)^2 + \left(P_{m3h} - a_3 - b_3 P_{m3h}\right)^2 + \right.$$

$$\left. + \left(P_{m4h} - a_4 - b_4 P_{m4h}\right)^2 \right] \tag{14}$$

Differentiate with respect to a_3 , a_4 , b_3 , b_4

$$\frac{\partial F_p}{\partial a_3} = 0 \qquad \frac{\partial F_p}{\partial b_3} = 0 \qquad \frac{\partial F_p}{\partial a_4} = 0 \qquad \frac{\partial F_p}{\partial b_4} = 0 \tag{15}$$

Then,

$$\frac{\partial F_p}{\partial a_3} = \sum_{h=1}^{H}\left[\left(P_{c1h} + P_{c2h} + a_3 + b_3 P_{m3h} + a_4 + b_4 P_{m4}\right) - \left(P_{m3h} - a_3 - b_3 P_{m3h}\right)\right] = 0$$

$$\frac{\partial F_p}{\partial a_4} = \sum_{h=1}^{H}\left[\left(P_{c1h} + P_{c2h} + a_3 + b_3 P_{m3h} + a_4 + b_4 P_{m4h}\right) - \left(P_{m4h} - a_4 - b_4 P_{m4h}\right)\right] = 0 \tag{16}$$

$$\frac{\partial F_p}{\partial b_3} = \sum_{h=1}^{H}\left[\left(P_{c1h} + P_{c2h} + a_3 + b_3 P_{m3h} + a_4 + b_4 P_{m4h}\right)P_{m3h} - \left(P_{m3h} - a_3 - b_3 P_{m3h}\right)P_{m3h}\right] = 0$$

$$\frac{\partial F_p}{\partial b_4} = \sum_{h=1}^{H}\left[\left(P_{c1h} + P_{c2h} + a_3 + b_3 P_{m3h} + a_4 + b_4 P_{m4h}\right)P_{m4h} - \left(P_{m4h} - a_4 - b_4 P_{m4h}\right)P_{m4h}\right] = 0$$

Rearranging the above equations

$$\sum_{h=1}^{H}\left[(2a_3) + (2b_3 P_{m3h}) + (a_4) + (b_4 P_{m4h})\right] = \sum_{h=1}^{H}\left(P_{m3h} - P_{c1h} - P_{c2h}\right)$$

$$\sum_{h=1}^{H}\left[(a_3) + (b_3 P_{m3h}) + (2a_4) + (2b_4 P_{m4h})\right] = \sum_{h=1}^{H}\left(P_{m4h} - P_{c1h} - P_{c2h}\right) \tag{17}$$

$$\sum_{h=1}^{H}\left[(2a_3 P_{m3h}) + (2b_3 P_{m3h}^2) + (a_4 P_{m3h}) + (b_4 P_{m4h} P_{m3h})\right] = \sum_{h=1}^{H}\left(P_{m3h} - P_{c1h} - P_{c2h}\right)P_{m3h}$$

$$\sum_{h=1}^{H}\left[(a_3 P_{m4h}) + (b_3 P_{m3h} P_{m4h}) + (2a_4 P_{m4h}) + (2b_4 P_{m4h}^2)\right] = \sum_{h=1}^{H}\left(P_{m4h} - P_{c1h} - P_{c2h}\right)P_{m4h}$$

In matrix form, we have a 4x4 linear equation

$$\sum_{h=1}^{H}\begin{bmatrix} 2 & 2P_{m3h} & 1 & P_{m4h} \\ 1 & P_{m3h} & 2 & 2P_{m4h} \\ 2P_{m3h} & 2P_{m3h}^2 & P_{m3h} & P_{m3h}P_{m4h} \\ P_{m4h} & P_{m3h}P_{m4h} & 2P_{m4h} & 2P_{m4h}^2 \end{bmatrix}\begin{bmatrix} a_3 \\ b_3 \\ a_4 \\ b_4 \end{bmatrix} = \sum_{h=1}^{H}\begin{bmatrix} P_{m3h} - P_{c1h} - P_{c2h} \\ P_{m4h} - P_{c1h} - P_{c2h} \\ \left(P_{m3h} - P_{c1h} - P_{c2h}\right)P_{m3h} \\ \left(P_{m4h} - P_{c1h} - P_{c2h}\right)P_{m4h} \end{bmatrix} \tag{18}$$

Using the Gauss Method, we can solve this 4x4 Ax=B linear equation, and got real power coefficients of point 3 and 4. Likewise, the reactive power coefficients can be obtained. Note that A is nonsingular for more than one hour of data, provided that the data changes. The equation for the general case is shown below. The solution produces the calibration coefficients at all points of a bus, except the reliable points. It is important to have at least one reliable point at a bus which is to be calibrated by power balance constraint because the power reference level provided by the reliable points is needed to avoid a trivial solution.

$$\sum_{h=1}^{H}\begin{bmatrix} 2 & 1 & \cdots & 1_R & 2P_{R+1,h} & P_{R+2,h} & \cdots & P_{M,h} \\ 1 & 2 & \cdots & 1_R & P_{R+1,h} & 2P_{R+2,h} & \cdots & P_{M,h} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 2_R & P_{R+1,h} & P_{R+2,h} & \cdots & 2P_{M,h} \\ 2P_{R+1,h} & P_{R+1,h} & \cdots & P_{R+1,h} & 2P_{R+1,h}^2 & P_{R+1,h}P_{R+2,h} & \cdots & P_{R+1,h}P_{M,h} \\ P_{R+2,h} & 2P_{R+2,h} & \cdots & P_{R+2,h} & P_{R+2,h}P_{R+1,h} & 2P_{R+2,h}^2 & \cdots & P_{R+2,h}P_{M,h} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{M,h} & P_{M,h} & \cdots & 2P_{M,h} & P_{M,h}P_{R+1,h} & P_{M,h}P_{R+2,h} & \cdots & 2P_{M,h}^2 \end{bmatrix}\begin{bmatrix} a_{R+1} \\ a_{R+2} \\ \vdots \\ a_M \\ b_{R+1} \\ b_{R+2} \\ \vdots \\ b_M \end{bmatrix} = \mathbf{B} \tag{19}$$

$$\mathrm{B} = \sum_{h=1}^{H}\begin{bmatrix} P_{R+1,h} - \sum_{r=1}^{R} P_{r,h} \\ P_{R+2,h} - \sum_{r=1}^{R} P_{r,h} \\ \vdots \\ P_{M,h} - \sum_{r=1}^{R} P_{r,h} \\ P_{R+1,h}^2 - P_{R+1,h}\sum_{r=1}^{R} P_{r,h} \\ P_{R+2,h}^2 - P_{R+2,h}\sum_{r=1}^{R} P_{r,h} \\ \vdots \\ P_{M,h}^2 - P_{M,h}\sum_{r=1}^{R} P_{r,h} \end{bmatrix} \tag{20}$$

Similarly, we can write the linear equations of reactive power coefficients.

2.1.2 Current Equality Constraint

In the previous section, P and Q at a single bus were calibrated using the power balance constraint. In this section and the next section, a current equality constraint is used to establish the relationship between two buses, thus propagating the calibration work to another bus. In our simple system case, since the calibrated values of P and Q at one end of line 1 have been calculated and voltage at bus I is known, the current at both ends of the line can be calculated, and the difference between them should be zero. That means the current of point 3 should be equal to the current of point 5 in Figure 3.

$$I_3 - I_5 = 0 \tag{21}$$

Hence, we can write the objective function of current equality constraint :

$$\sqrt{\frac{P_{c3}^2 + Q_{c3}^2}{V_{c3}^2}} - \sqrt{\frac{(a_{25} + b_{25}P_{m5})^2 + (a_{35} + b_{35}Q_{m5})^2}{(a_{15} + b_{15}V_{m5})^2}} = \varepsilon_i \tag{22}$$

2.1.3 Power Loss Constraint

Like the current equality constraint, the power loss constraint can be used to build the relationship between two buses.

$$(I_3^2 + I_5^2)(R + X) = 2\left\|P_{c3}\right| - \left|P_{c5}\right\| + 2\left\|Q_{c3}\right| - \left|Q_{c5}\right\| \tag{23}$$

$$\left(\frac{P_{c3}^2 + Q_{c3}^2}{V_{c3}^2} + \frac{P_{c5}^2 + Q_{c5}^2}{V_{c5}^2}\right)(R + X) = 2\left\|P_{c3}\right| - \left|P_{c5}\right\| + 2\left\|Q_{c3}\right| - \left|Q_{c5}\right\| \tag{24}$$

and the equation (24) can be rewritten as follows:

$$\left(\frac{P_{c3}^2 + Q_{c3}^2}{V_{c3}^2} + \frac{(a_{25} + b_{25}P_{m5})^2 + (a_{35} + b_{35}Q_{m5})^2}{(a_{15} + b_{15}V_{m5})^2}\right)(R + X) - 2(|\Delta P| + |\Delta Q|) = \varepsilon_l \tag{25}$$

where $\Delta P = \left\| P_{c3} \right| - \left| a_{25} + b_{25} P_{m5} \right\|$

$$\Delta Q = \left\| Q_{c3} \right| - \left| a_{35} + b_{35} Q_{m5} \right\|$$

2.1.4 Voltage Drop Constraint

The voltage drop constraint can be used for establishing the voltage relationship between two buses. For our two bus system, the following equations are derived for this relationship. Let us consider line 2 between bus I and J.

Assume $\overline{V_4} = V_4 \angle \theta_4$; $\overline{V_6} = V_6 \angle 0$; $\ddot{I}_4 = I_4 \angle \beta_4$

$$V_6 + I_4 \angle \beta_4 (R + jX) - V_4 \angle \theta_4 = 0 \qquad (26)$$

Using the real part since it is more consequential for the voltage magnitudes,

$$\begin{aligned} &V_6 + I_4 R \cos\beta_4 - I_4 X \sin\beta_4 - V_4 \cos\theta_4 = 0 \\ &P_4 + jQ_4 = -V_4 I_4 \angle(\theta_4 - \beta_4) \\ &P_6 + jQ_6 = V_6 I_4 \angle - \beta_4 \end{aligned} \qquad (27)$$

Equation (27) can be rewritten as

$$\begin{aligned} &P_6 + jQ_6 = V_6 I_4 \cos\beta_4 - jV_6 I_4 \sin\beta_4 \\ \text{where} \quad &\cos\beta_4 = \frac{P_6}{V_6 I_4} \\ &\sin\beta_4 = -\frac{Q_6}{V_6 I_4} \end{aligned} \qquad (28)$$

Substituting equations (28) into (27), we have:

$$
\begin{aligned}
P_4 &= -V_4 I_4 \cos(\theta_4 - \beta_4) \\
P_4 &= -\frac{V_4 P_6}{V_6}\cos\theta_4 + \frac{V_4 Q_6}{V_6}\sin\theta_4 \\
Q_4 &= -\frac{V_4 P_6}{V_6}\sin\theta_4 - \frac{V_4 Q_6}{V_6}\cos\theta_4
\end{aligned} \tag{29}
$$

Solving equations (29) for cos.θ4 ,

$$
\cos\theta_4 = -\frac{P_4 P_6 + Q_4 Q_6}{P_6^2 + Q_6^2}\frac{V_6}{V_4} \tag{30}
$$

Substituting (28) and (30) into (27) gets

$$
V_6 + I_4 A_6 + V_4 B_6 = 0 \tag{31}
$$

where

$$
\begin{aligned}
A_6 &= \frac{(RP_{m6} + XQ_{m6})}{\sqrt{P_{m6}^2 + Q_{m6}^2}} \\
I_{ij} &= I_4 = \frac{\sqrt{P_{c4}^2 + Q_{c4}^2}}{V_{c4}} \\
B_6 &= \frac{(P_{c4} P_{m6} + Q_{c4} Q_{m6})}{\sqrt{P_{c4}^2 + Q_{c4}^2}\sqrt{P_{m6}^2 + Q_{m6}^2}}
\end{aligned}
$$

In general form, we can rewrite above equations as follows:

$$
V_{mj} + I_{ij} A_j + V_{ci} B_j = 0 \tag{32}
$$

The corresponding error is given by

$$
\varepsilon_{vj} = (V_{mj} + I_{ij} A_j + V_{ci} B_j) \tag{33}
$$

$$A_j = \frac{\left(RP_{mj} + XQ_{mj}\right)}{\sqrt{P_{mj}^2 + Q_{mj}^2}}$$

where
$$I_{ij} = \frac{\sqrt{P_{ci}^2 + Q_{ci}^2}}{V_{ci}}$$

$$B_j = \frac{\left(P_{ci}P_{mj} + Q_{ci}Q_{mj}\right)}{\sqrt{P_{ci}^2 + Q_{ci}^2}\sqrt{P_{mj}^2 + Q_{mj}^2}}$$

For the line between point 3 and 5 in the simple system of Figure 3, substituting A_5 ,B_5, and I_{35} in the above general form.

2.1.5 Combination of Constraints

Four constraints were expounded in the preceding sections and now the question arises on how to use them to effect the calibration.

The power balance constraint can be used for calibrating the P and Q measurements at individual buses. This step is followed by current equality, power loss and voltage drop constraints to reach out to other buses where the first step was not possible.

The current equality, power loss, voltage drop constraints can establish the relationship between any two buses of a system. At least two of them are used in order to enhance the reliability of the calibration process. It is felt that in any case the voltage drop constraint must be present. Three combinations are thus possible:

(1) Current Equality + Voltage Drop for point j

$$\varepsilon_j^2 = \varepsilon_{ij}^2 + \varepsilon_{vj}^2 \tag{34}$$

(2) Power Loss + Voltage Drop for point j

$$\varepsilon_j^2 = \varepsilon_{lj}^2 + \varepsilon_{vj}^2 \tag{35}$$

(3) Current Equality + Power Loss + Voltage Drop for point j

$$\varepsilon_j^2 = \varepsilon_{ij}^2 + \varepsilon_{lj}^2 + \varepsilon_{vj}^2 \tag{36}$$

2.2 Nonlinear Least Squares (UNSLF Routine of IMSL)

The IMSL FORTRAN Numerical Library is a comprehensive resource of more than 900 FORTRAN subroutines for applications in general applied mathematics. In Section 2.1, the mathematical model for our study was introduced. In our program, the UNSLF of IMSL is used to solve the error minimizatio problem. The results were quite satisfactory. UNSLF can solve a nonlinear least squares problem using a modified Levenberg-Marquartdt algorithm and a finite-difference Jacobian.

Usage:

CALL UNSLF (FCN, M, N, XGUESS, XSCALE, FSCALE, IPRAM,

RPRAM, X, FVEC, FJAC, LDFJAC)

Algorithm:

UNSLF is based on the MINPACK routine LMDIF by More et al. (1980). It uses a modified Levenberg-Marquardt method to solve nonlinear least squares problems. The problem is stated as follows:

$$\min_{x \in IR^n} \frac{1}{2} F(x)^T F(x) = \frac{1}{2} \sum_{i=1}^{m} f_i(x)^2 \tag{37}$$

where $m \geq n, F: IR^n \rightarrow IR^m$, and $f_i(x)$ is the i-th component function of F(x). From a current point, the algorithm uses the trust region approach:

$$\min_{x_n \in IR^n} \|F(x_c) + J(x_c)(x_n - x_c)\|_2 \tag{38}$$

subject to $\|x_n - x_c\|_2 \leq \delta_c$

to get a new point x_n , which is computed as

$$x_n = x_c - (J(x_c)^T J(x_c) + \mu_c I)^{-1} J(x_c)^T F(x_c), \tag{39}$$

where μ_c=0 if $\delta_c \geq \|(J(x_c)^T J(x_c))^{-1} J(x_c)^T F(x_c)\|_2$ *and* μ_c>0 otherwise. $F(x_c)$ and $J(x_c)$ are the function values and the Jacobian evaluated at the current point x_c , respectively. This procedure is repeated until the stopping criteria are satisfied.

Since a finite-difference method is used to estimate the Jacobian, for some single precision calculations, an inaccurate estimate of Jacobian may cause the algorithm to terminate at a noncritical point. In such cases high precision arithmetic is recommended. Also, whenever the exact Jacobian can be easily provided, IMSL routine UNSLF should be used instead by DUNLSF routine.

2.3 Solution Algorithm and Program Flow Chart

2.3.1 Algorithm

The measurement calibration algorithm is now described. It requires at the outset the specification of reliable points and numbering of all the measurement points.

Step 1: Determine the position of all reliable ponits at each bus of the power system.

Step 2 : For every line terminated with a single reliable point, carry out a current-equality/voltage-drop or power-loss/voltage-drop or all of three constraint minimization.

The outcome of this step are the calibration coefficients of real power, the reactive power and the voltage at the other end of the line, i.e., the uncalibrated point. These constants are used to calibrate the measured values at the bus of the uncalibrated point. This step is performed for all similar lines before proceeding to step 3.

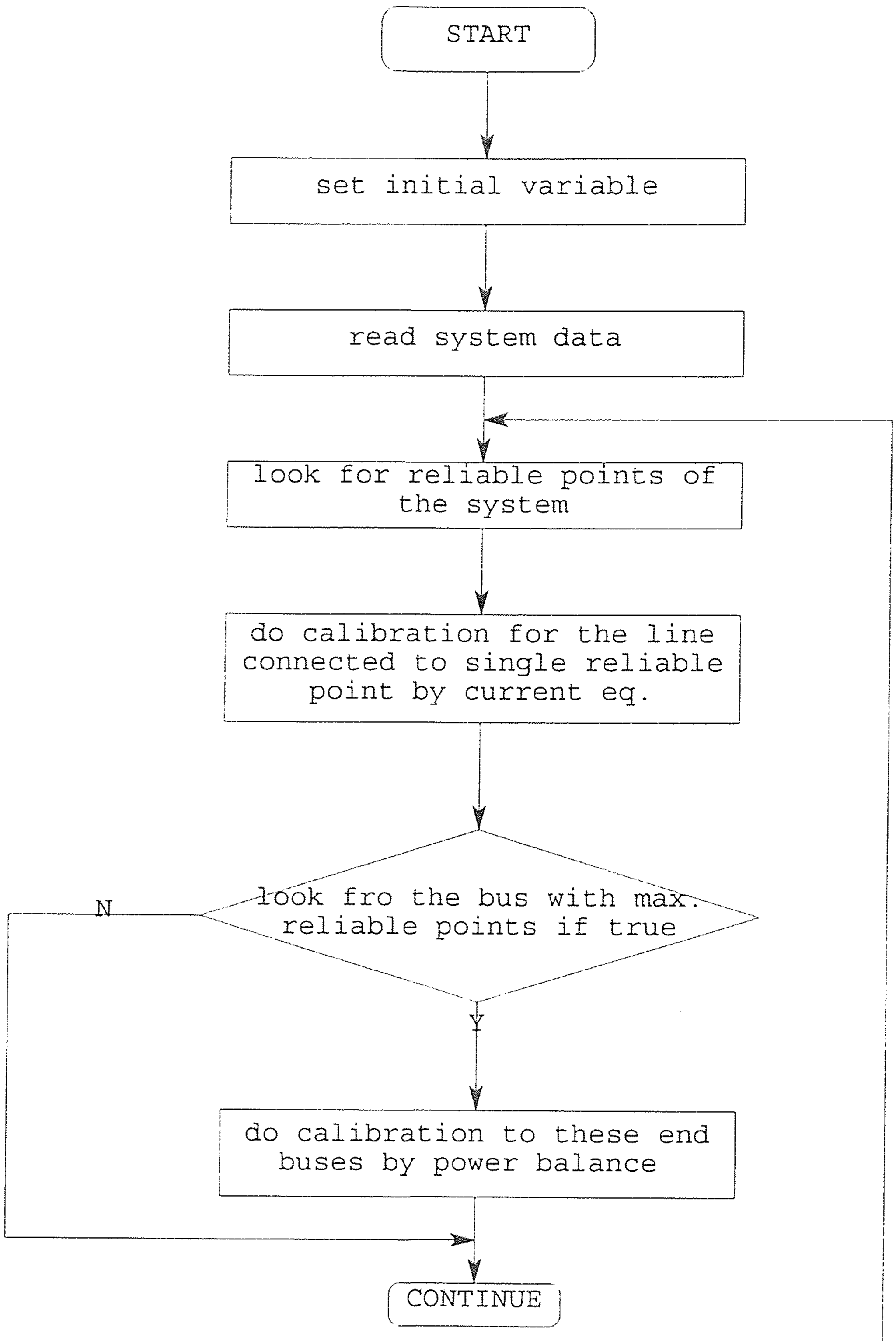
Step 3 : Select the bus with the maximum number of reliable points, say bus I. Carry out a power balance constraint error minimization, involving all points at the bus I over all hourly measurements. The outcome of this procedure are the calibration constants which are used to calibrate all of the power and reactive power measurements but the reliable points associated with bus I.

Step 4 : Identify all lines connected to bus I which have an uncalibrated point at their other end. Carry out a current-equality/voltage drop or power-loss/voltage-drop constraint

minimization by considering the previously calibrated end as reliable. The outcome of this step are the calibration coefficients of the real power, reactive power and voltage at the other end of the lines connected to bus I.

Step 5 : If all measurement points have been calibrated, stop

2.3.2 Program Flow Chart



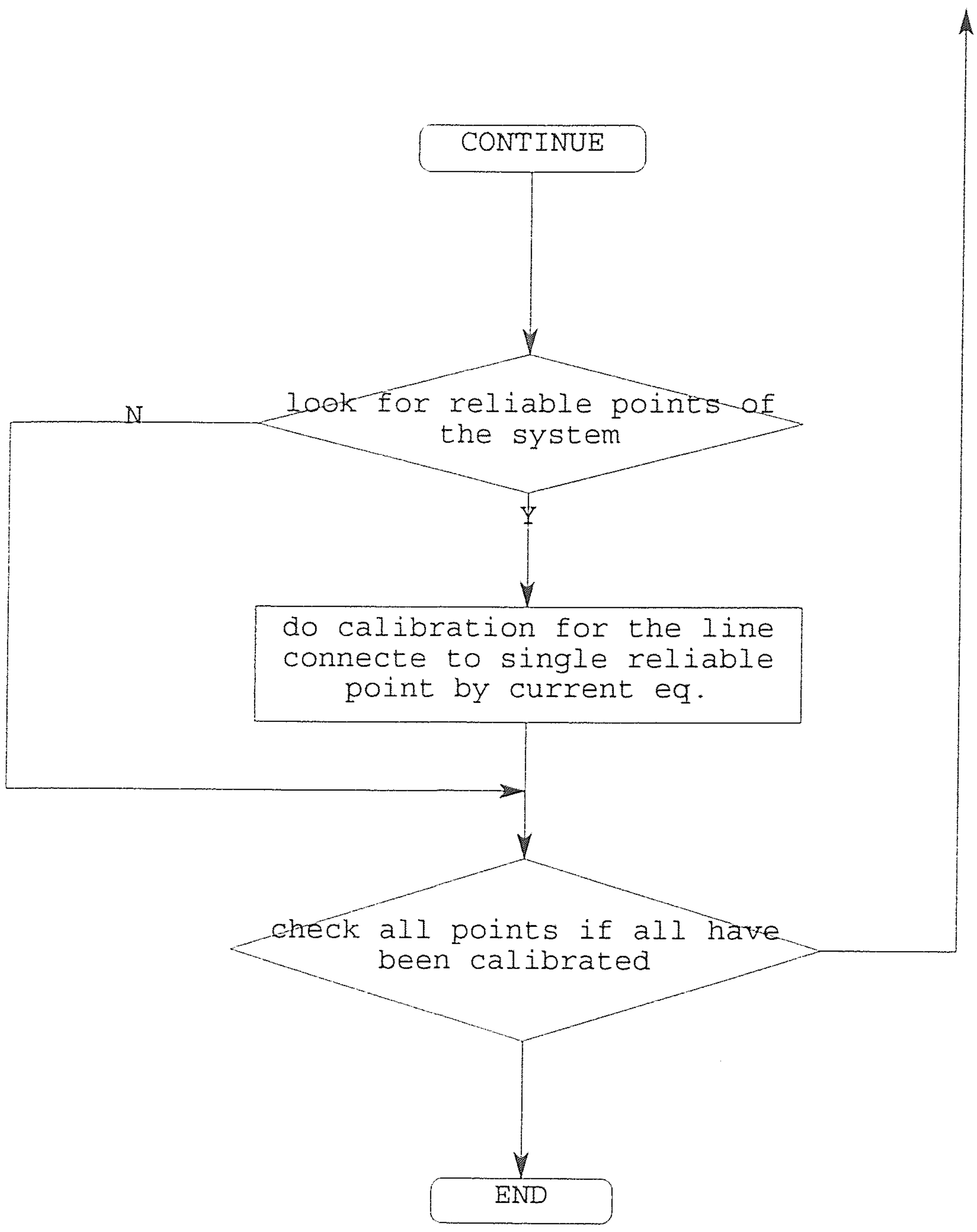


Table 1 Program Flow Chart

CHAPTER 3

CASE STUDY

3.1 Simple System Case

In Figure 3, a simple two bus system is given to test the algorithm. First the system measurement data are prepared in per unit. These measurement data are obtained from a correct load flow program which produces " actual data". The latter are systematically modified by means of chosen calibration coefficients. These calibration coefficients are kept the same over the hours of each measurement location, but differ from one location to the other.

Procedure 1

In our case, point 1 and 2 are reliable points, The total least-square error minimization produced a_{23} ,a_{24} , b_{23} , b_{24} , a_{33} , a_{34}, b_{33} , b_{34} . These coefficients are used to calibrate the P and Q measurements at points 3 and 4. Once calibrated , points 3 and 4 become reliable points. Table 1 shows the measured, calibrated, and actual values of points 3 and 4. The plots clearly demonstrate that the measurement data have improved after calibration, getting close to the actual values.

Table 2 Measured, Calibrated, Actual Values of P, Q, V at Points 3 and 4

Hour	PM(3)	PC(3)	actual
1	-0.1738	-0.2001	-0.1931
2	-0.2089	-0.2355	-0.2281
3	-0.4043	-0.4323	-0.4227
4	-0.4995	-0.5282	-0.5175
5	-0.2616	-0.2885	-0.2806
6	-0.1915	-0.2179	-0.2108
7	-0.1461	-0.1722	-0.1655
8	-0.2836	-0.3107	-0.3025
9	-0.4502	-0.4785	-0.4684
10	-0.4567	-0.4851	-0.4749
11	-0.5204	-0.5493	-0.5383
12	-0.3389	-0.3664	-0.3575
13	-0.3389	-0.3664	-0.3575
14	-0.1775	-0.2038	-0.1967
15	-0.6188	-0.6484	-0.6363

Hour	PM(4)	PC(4)	actual
1	-0.1599	-0.1863	-0.1931
2	-0.1942	-0.2208	-0.2281
3	-0.385	-0.413	-0.4227
4	-0.478	-0.5066	-0.5175
5	-0.2457	-0.2727	-0.2806
6	-0.1772	-0.2037	-0.2108
7	-0.1328	-0.159	-0.1655
8	-0.2671	-0.2942	-0.3025
9	-0.4298	-0.4581	-0.4684
10	-0.4362	-0.4645	-0.4749
11	-0.4984	-0.5272	-0.5383
12	-0.3211	-0.3486	-0.3575
13	-0.3211	-0.3486	-0.3575
14	-0.1635	-0.1899	-0.1967
15	-0.5944	-0.6238	-0.6363

Hour	QM(3)	QC(3)	actual
1	-0.1598	-0.1714	-0.1705
2	-0.1533	-0.1648	-0.164
3	-0.1286	-0.1399	-0.1394
4	-0.0732	-0.084	-0.0841
5	-0.1506	-0.1621	-0.1613
6	-0.2144	-0.2264	-0.2249
7	-0.1199	-0.1311	-0.1307
8	-0.1556	-0.1671	-0.1663
9	-0.1745	-0.1862	-0.1851
10	-0.1715	-0.1832	-0.1822
11	-0.1938	-0.2056	-0.2045
12	-0.1395	-0.1509	-0.1502
13	-0.1395	-0.1509	-0.1502
14	-0.1613	-0.1729	-0.172
15	-0.205	-0.2169	-0.2156

Hour	QM(4)	QC(4)	actual
1	-0.1574	-0.169	-0.1705
2	-0.151	-0.1625	-0.164
3	-0.1268	-0.1381	-0.1394
4	-0.0726	-0.0834	-0.0841
5	-0.1483	-0.1598	-0.1613
6	-0.2107	-0.2227	-0.2249
7	-0.1183	-0.1295	-0.1307
8	-0.1532	-0.1647	-0.1663
9	-0.1717	-0.1834	-0.1851
10	-0.1688	-0.1805	-0.1822
11	-0.1906	-0.2024	-0.2045
12	-0.1375	-0.1489	-0.1502
13	-0.1375	-0.1489	-0.1502
14	-0.1588	-0.1704	-0.172
15	-0.2015	-0.2134	-0.2156

Hour	VM(3)	VC(3)	actual
1	0.9625	0.99	0.99
2	0.9526	0.98	0.98
3	0.9427	0.97	0.97
4	0.9625	0.99	0.99
5	0.9724	1	1
6	0.9921	1.02	1.02
7	1.002	1.03	1.03
8	1.0118	1.04	1.04
9	0.9526	0.98	0.98
10	0.9427	0.97	0.97
11	0.9408	0.968	0.968
12	0.9625	0.99	0.99
13	0.9625	0.99	0.99
14	0.9724	1	1
15	0.9427	0.97	0.97

Hour	VM(4)	VC(4)	actual
1	0.9539	0.99	0.97
2	0.9441	0.98	0.96
3	0.9343	0.97	0.95
4	0.9539	0.99	0.975
5	0.9637	1	0.98
6	0.9833	1.02	0.995
7	0.9931	1.03	1.015
8	1.0029	1.04	1.02
9	0.9441	0.98	0.955
10	0.9343	0.97	0.945
11	0.9324	0.968	0.94
12	0.9539	0.99	0.97
13	0.9539	0.99	0.97
14	0.9637	1	0.98
15	0.9343	0.97	0.94

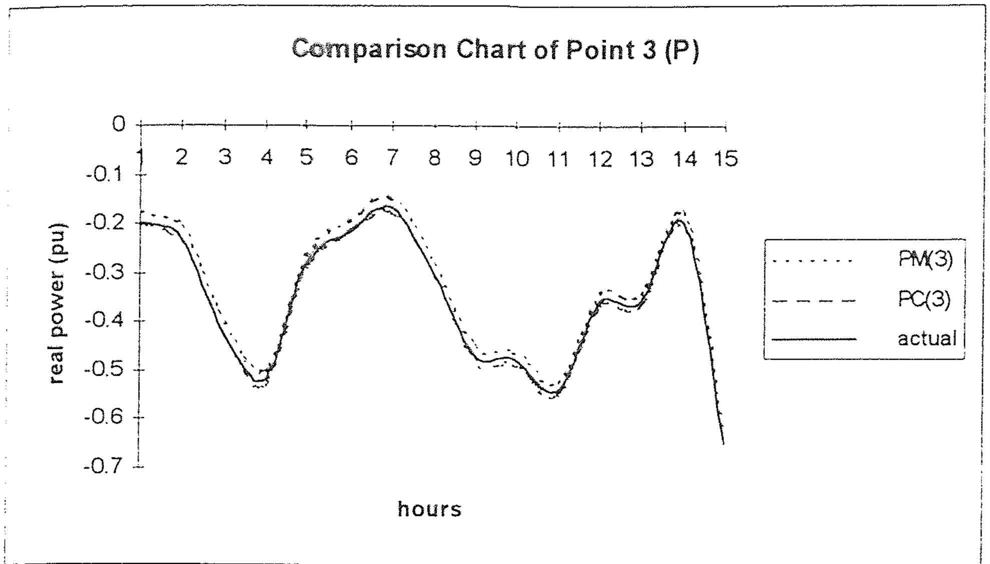


Figure 4 Comparison Chart of Measured, Calibrated and Actual P at Point 3

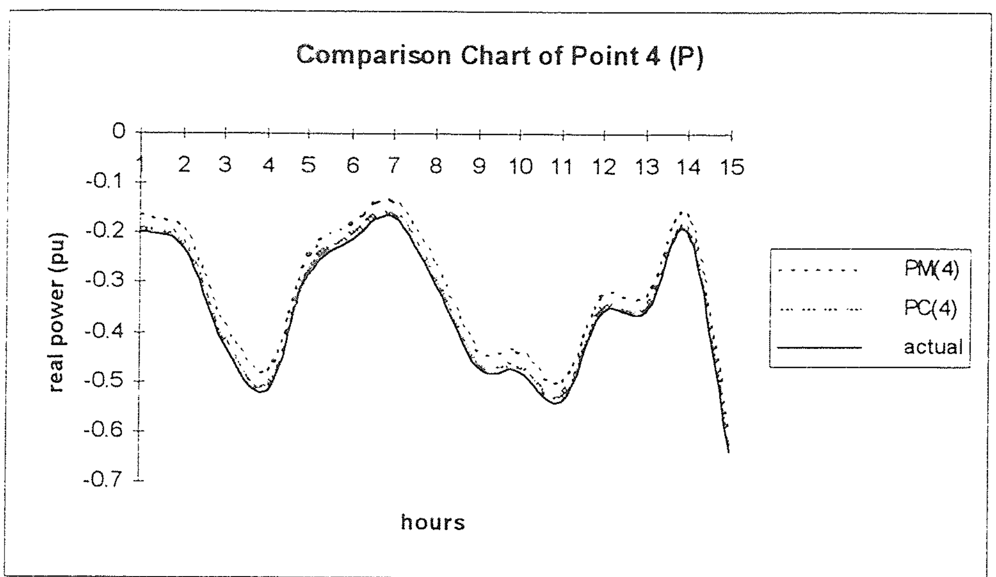


Figure 5 Comparison Chart of Measured, Calibrated and Actual P at Point 4

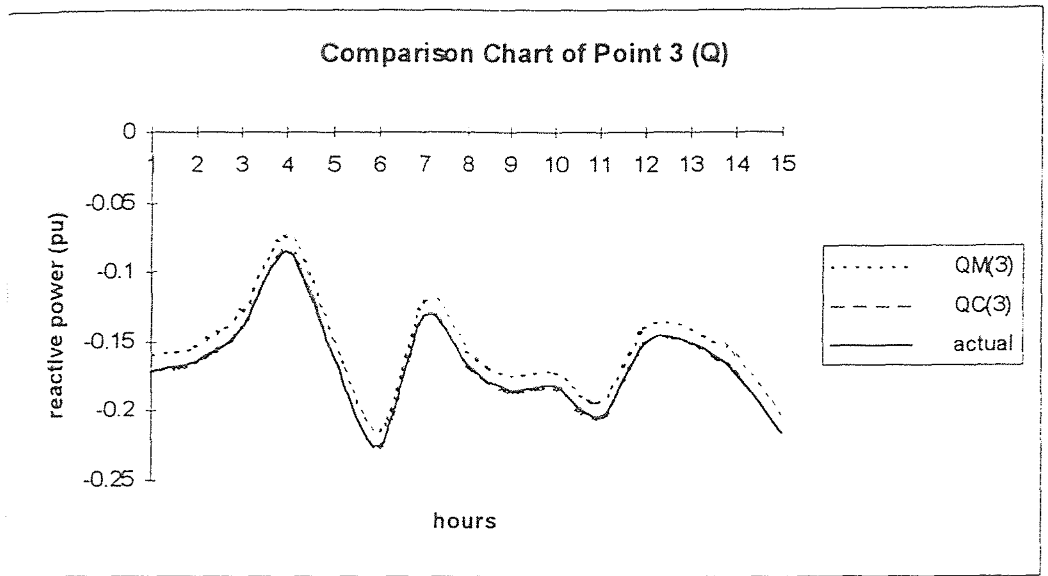


Figure 6 Comparison Chart of Measured, Calibrated and Actual Q at Point 3

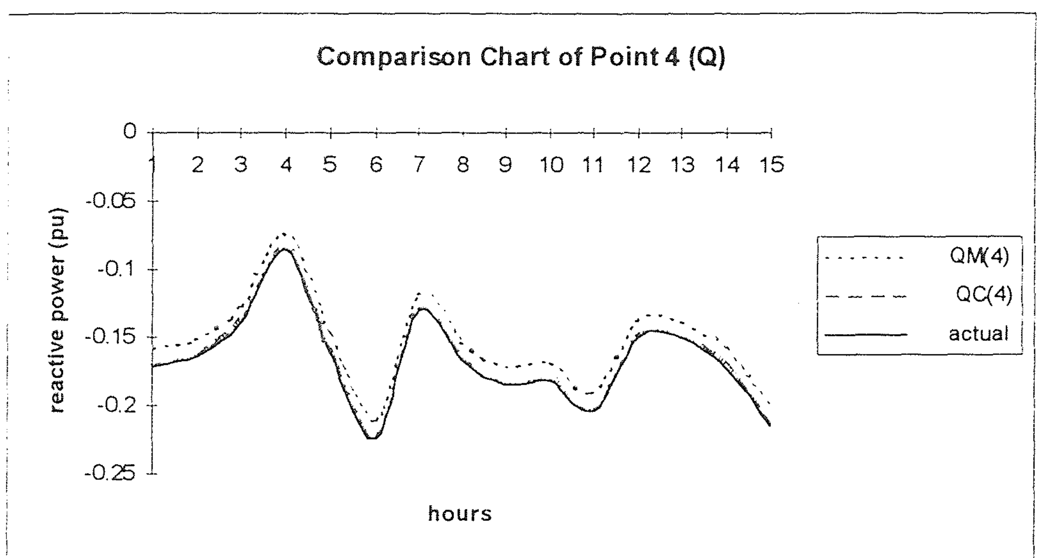


Figure 7 Comparison Chart of Measured, Calibrated and Actual Q at Point 4

Procedure 2

Once calibration is done at points 3 and 4, they become reliable points. At the other bus, points 5 and 6 are connected to points 3 and 4. Current equality and voltage drop constraints as objective functions are used to minimize by Least Square Method (UNSLF of IMSL Math Library) over 15 hours of measurement. The calibrated coefficients obtained for points 5 and 6, i.e., (a_{15}, a_{25}, a_{35}, b_{15}, b_{25}, b_{35}) and (a_{16}, a_{26}, a_{36}, b_{16}, b_{26}, b_{36}) are used to obtain the calibrated values of P, Q, V at points 5 and 6. Considering then P, Q, V of points 5 and 6 as reliable points, power balance constraint is used to do calibration at bus J. The calibrated coefficients of P and Q are then obtained for point 7. Thus all calibration at points 5, 6 and 7 are effected except the voltage measurement of point 7; but the latter may be taken as the average of the two calibrated voltages at points 5 and 6 as the bus voltage. i.e. , $V_5=V_6=V_7=V_{average}$.

The measured, calibrated , and actual values of P, Q, V at points 5 and 6 are shown in Table 2 .The plots indicate that all measurement data have been greatly improved after calibration.

Table 3 Measured, Calibrated, and Actual Values of P, Q, V at Point 5 and 6

Hour	PM(5)	PC(5)	actual
1	0.1677	0.1969	0.1921
2	0.2018	0.2326	0.2269
3	0.3907	0.4302	0.4195
4	0.4827	0.5265	0.5133
5	0.253	0.2862	0.279
6	0.1847	0.2147	0.2094
7	0.141	0.169	0.1649
8	0.2743	0.3085	0.3008
9	0.4348	0.4764	0.4645
10	0.4409	0.4827	0.4708
11	0.502	0.5466	0.533
12	0.3276	0.3642	0.3552
13	0.3276	0.3642	0.3552
14	0.1713	0.2007	0.1957
15	0.5962	0.6452	0.6291

Hour	PM(6)	PC(6)	actual
1	0.1554	0.1835	0.192
2	0.1892	0.2184	0.227
3	0.3762	0.4112	0.419
4	0.4673	0.5051	0.513
5	0.2398	0.2705	0.279
6	0.1722	0.2009	0.209
7	0.129	0.1563	0.164
8	0.261	0.2924	0.3
9	0.4199	0.4562	0.464
10	0.426	0.4625	0.47
11	0.4864	0.5248	0.533
12	0.3138	0.3468	0.355
13	0.3138	0.3468	0.355
14	0.159	0.1873	0.195
15	0.5797	0.6209	0.629

Hour	QM(5)	QC(5)	actual
1	0.1444	0.1687	0.1637
2	0.1367	0.1608	0.1558
3	0.1003	0.1234	0.1183
4	0.0398	0.0612	0.056
5	0.1318	0.1558	0.1508
6	0.1949	0.2206	0.2158
7	0.1083	0.1316	0.1265
8	0.1362	0.1603	0.1552
9	0.1395	0.1637	0.1587
10	0.1356	0.1597	0.1547
11	0.1496	0.1741	0.1691
12	0.1164	0.1399	0.1349
13	0.1164	0.1399	0.1349
14	0.1458	0.1701	0.1652
15	0.1482	0.1726	0.1676

Hour	QM(6)	QC(6)	actual
1	0.1318	0.1687	0.163
2	0.1239	0.1608	0.155
3	0.087	0.1234	0.118
4	0.0257	0.0612	0.056
5	0.119	0.1558	0.15
6	0.183	0.2206	0.215
7	0.0951	0.1316	0.126
8	0.1234	0.1603	0.155
9	0.1268	0.1637	0.158
10	0.1229	0.1597	0.154
11	0.137	0.1741	0.169
12	0.1033	0.1399	0.134
13	0.1033	0.1399	0.134
14	0.1332	0.1701	0.165
15	0.1356	0.1726	0.167

Hour	VM(5)	VC(5)	actual
1	0.952	0.9752	0.97
2	0.942	0.9659	0.96
3	0.9319	0.956	0.95
4	0.957	0.9799	0.975
5	0.962	0.9845	0.98
6	0.9771	0.9986	0.995
7	0.9972	1.0173	1.01
8	1.0022	1.0219	1.02
9	0.9369	0.9612	0.955
10	0.9269	0.9519	0.945
11	0.9219	0.9472	0.94
12	0.952	0.9752	0.97
13	0.952	0.9752	0.97
14	0.962	0.9845	0.98
15	0.9219	0.9472	0.94

Hour	VM(6)	VC(6)	actual
1	0.9406	0.9748	0.97
2	0.9307	0.9655	0.96
3	0.9208	0.9561	0.95
4	0.9455	0.9795	0.975
5	0.9505	0.9842	0.98
6	0.9653	0.9982	0.995
7	0.9851	1.017	1.01
8	0.9901	1.0217	1.02
9	0.9257	0.9607	0.955
10	0.9158	0.9513	0.945
11	0.9109	0.9467	0.94
12	0.9406	0.9748	0.97
13	0.9406	0.9748	0.97
14	0.9505	0.9842	0.98
15	0.9109	0.9467	0.94

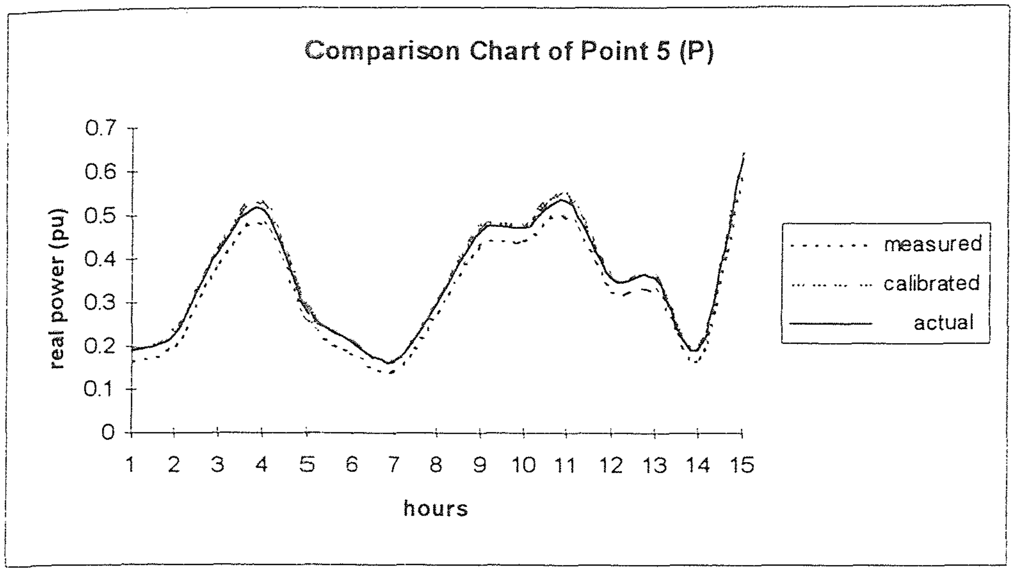


Figure 8 Comparison Chart of measured, Calibrated and Actual P at Point 5

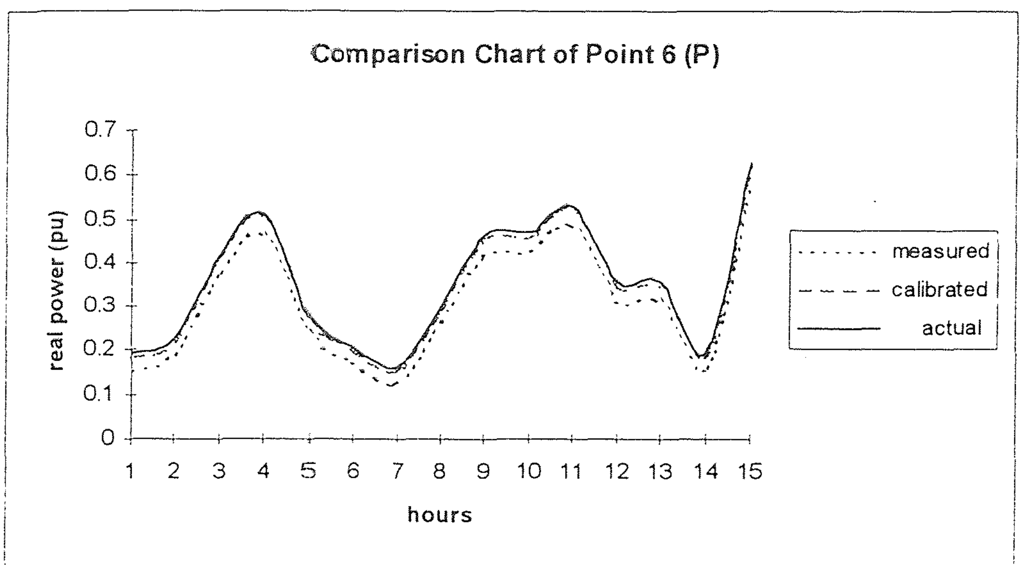


Figure 9 Comparison Chart of Measured, Calibrated and Actual P at Point 6

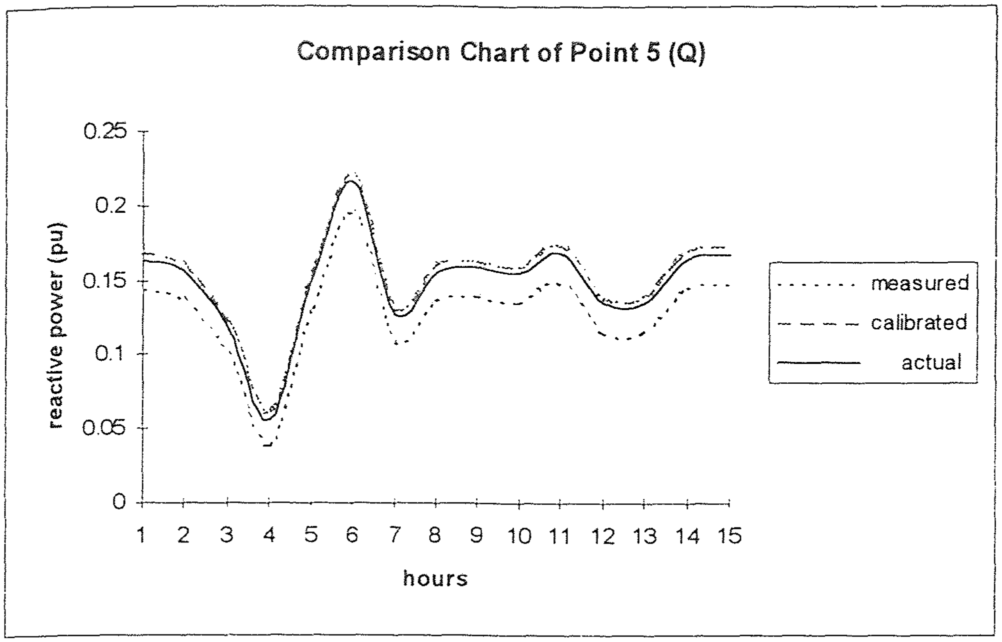


Figure 10 Comparison Chart of Measured, Calibrated and Actual Q at Point 5

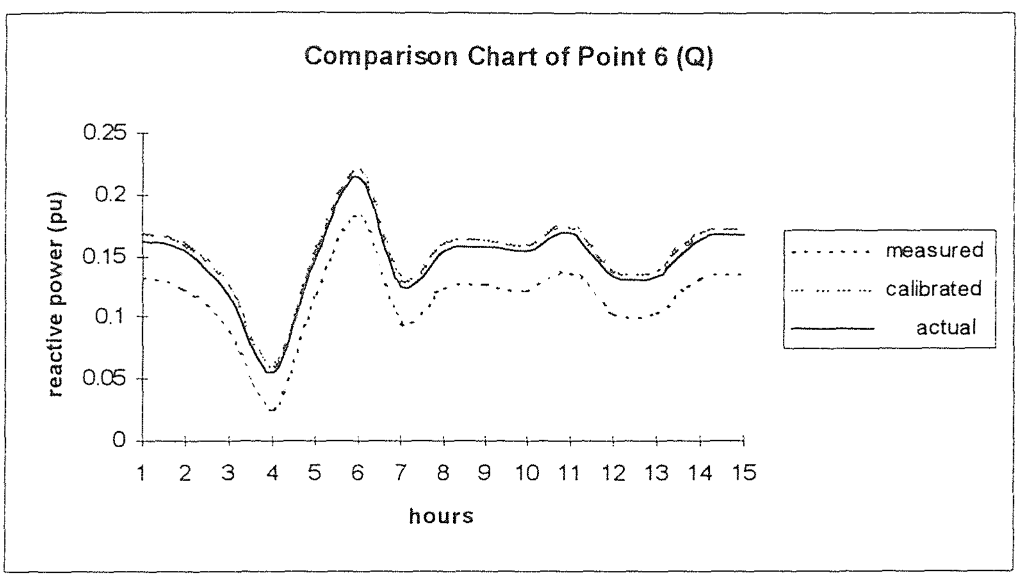


Figure 11 Comparison Chart of Measured, Calibrated and Actual Q at Point 6

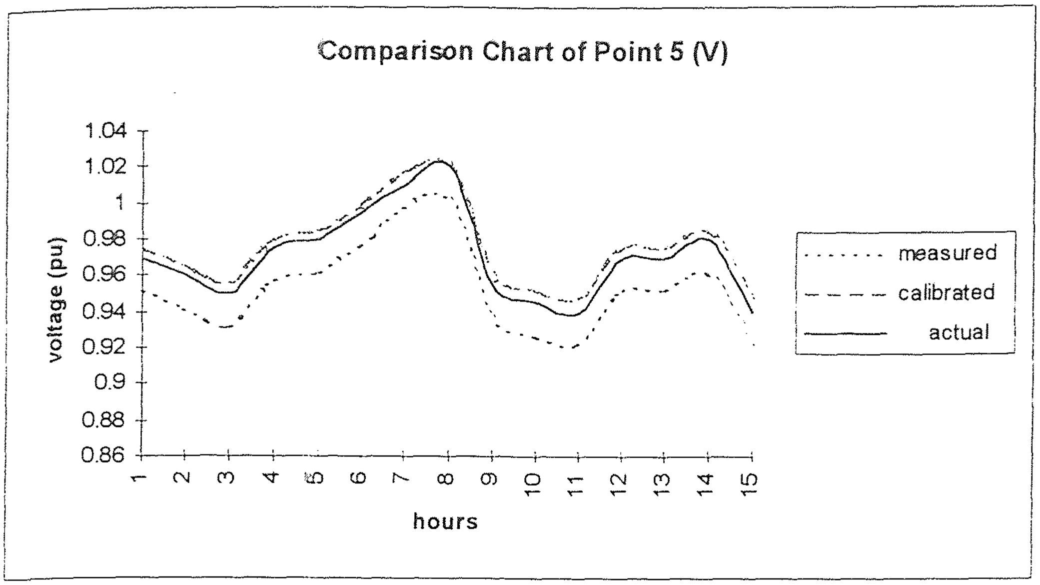


Figure 12 Comparison Chart of Measured, Calibrated and Actual V at Point 5

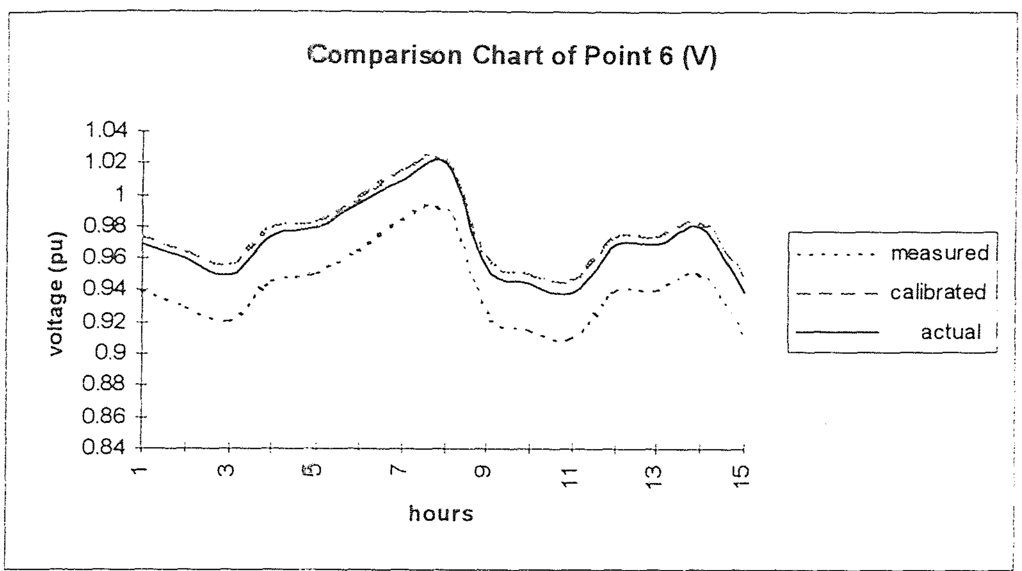
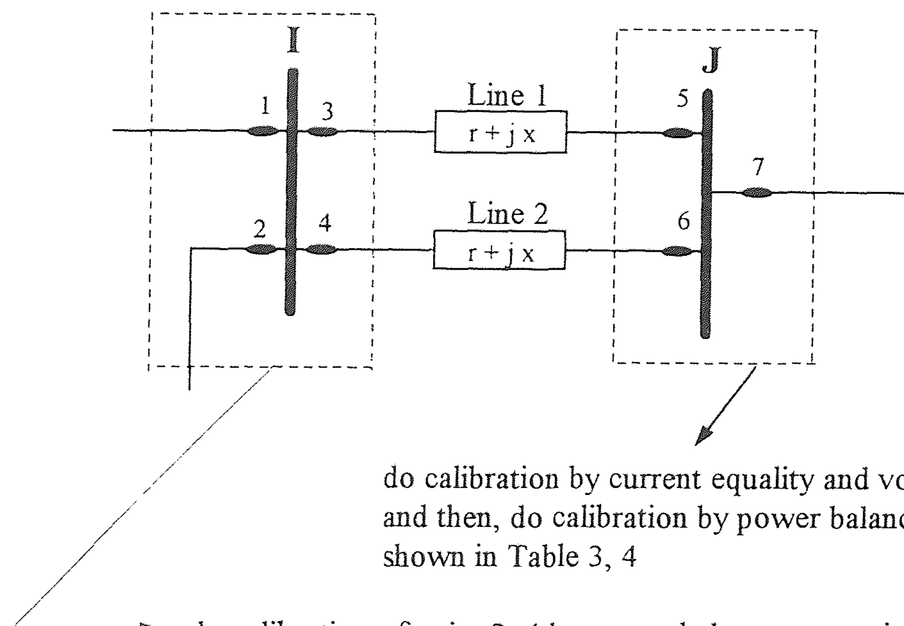


Figure 13 Comparison Chart of Measured, Calibrated and Actual V at Point 6

Table 4 Measured, Calibrated, and Actual Values of P and Q at Point 7

Hour	PM(7)	PC(7)	actual	Hour	QM(7)	QC(7)	Actual
1	-0.3417	-0.3812	-0.384	1	-0.3014	-0.3312	-0.327
2	-0.4106	-0.4515	-0.453	2	-0.2858	-0.3155	-0.311
3	-0.7921	-0.8409	-0.839	3	-0.2124	-0.2415	-0.236
4	-0.9779	-1.0305	-1.02	4	-0.0903	-0.1185	-0.112
5	-0.5139	-0.5569	-0.558	5	-0.2761	-0.3057	-0.301
6	-0.376	-0.4162	-0.418	6	-0.4035	-0.4342	-0.431
7	-0.2879	-0.3263	-0.329	7	-0.2284	-0.2577	-0.253
8	-0.5571	-0.601	-0.601	8	-0.2848	-0.3145	-0.31
9	-0.8811	-0.9317	-0.928	9	-0.2916	-0.3214	-0.317
10	-0.8936	-0.9444	-0.941	10	-0.2837	-0.3134	-0.309
11	-1.0169	-1.0703	-1.06	11	-0.3119	-0.3418	-0.338
12	-0.6648	-0.7109	-0.71	12	-0.2449	-0.2743	-0.269
13	-0.6648	-0.7109	-0.71	13	-0.2449	-0.2743	-0.269
14	-0.3489	-0.3885	-0.391	14	-0.3042	-0.3341	-0.33
15	-1.2072	-1.2645	-1.25	15	-0.309	-0.3389	-0.335



do calibration by current equality and voltage drop first, and then, do calibration by power balance, results are shown in Table 3, 4

do calibration of point 3, 4 by power balance constraint, results are shown in Table 2

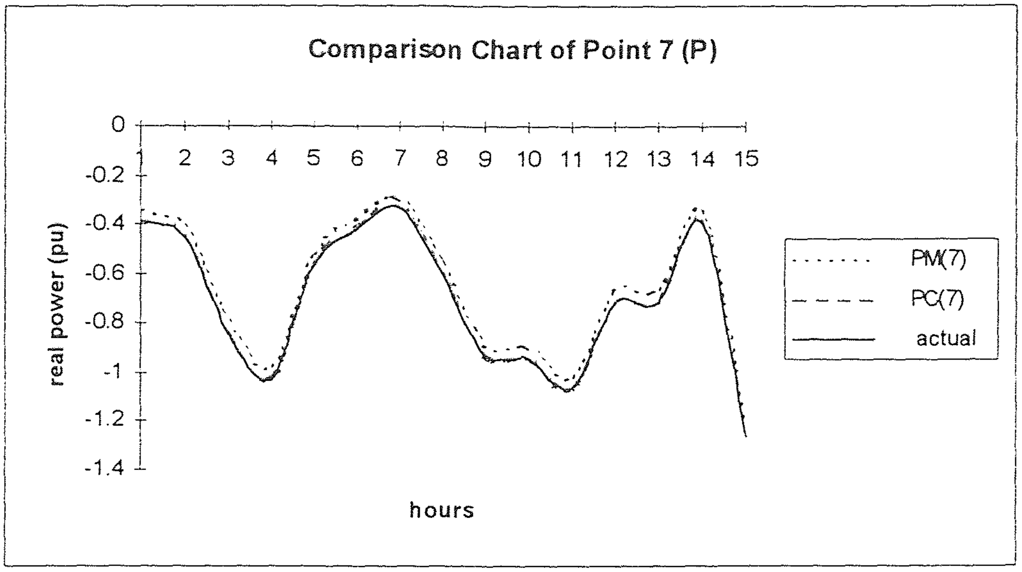


Figure 14 Comparison Chart of Measured, Calibrated and Actual P at Point 7

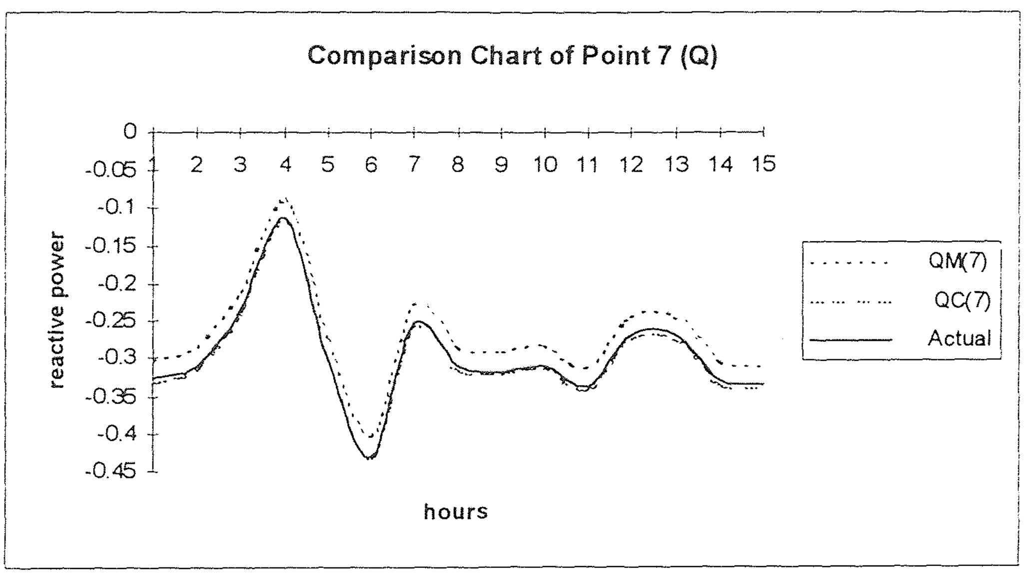


Figure 15 Comparison Chart of Measured, Calibrated and Actual Q at Point 7

Procedure 3

As we did in last two procedures, well improved measurement data of points 3, 4, 5, 6, 7 have been obtained by using power balance and current-equality/voltage-drop constriants.

Here, we change to use power-loss/voltage-drop constraint to expand to other end bus connected to reliable points. The results are shown in Table 5, 6 compared with current-equality/voltage-drop constraint. The comparison charts are ploted as follows.

Table 5 Calibrated Results (P , Q) of Current Equality and Power Loss at Point 7

Hour	PM(7)	PCI(7)	PCL(7)	Actual	QM(7)	QCI(7)	QCL(7)	Actual
1	-0.3417	-0.3812	-0.381	-0.384	-0.3014	-0.3312	-0.3276	-0.327
2	-0.4106	-0.4515	-0.4505	-0.453	-0.2858	-0.3155	-0.3117	-0.311
3	-0.7921	-0.8409	-0.8352	-0.839	-0.2124	-0.2415	-0.237	-0.236
4	-0.9779	-1.0305	-1.0226	-1.02	-0.0903	-0.1185	-0.1126	-0.112
5	-0.5139	-0.5569	-0.5546	-0.558	-0.2761	-0.3057	-0.3018	-0.301
6	-0.376	-0.4162	-0.4156	-0.418	-0.4035	-0.4342	-0.4316	-0.431
7	-0.2879	-0.3263	-0.3267	-0.329	-0.2284	-0.2577	-0.2533	-0.253
8	-0.5571	-0.601	-0.5982	-0.601	-0.2848	-0.3145	-0.3107	-0.31
9	-0.8811	-0.9317	-0.925	-0.928	-0.2916	-0.3214	-0.3176	-0.317
10	-0.8936	-0.9444	-0.9376	-0.941	-0.2837	-0.3134	-0.3096	-0.309
11	-1.0169	-1.0703	-1.0619	-1.06	-0.3119	-0.3418	-0.3383	-0.338
12	-0.6648	-0.7109	-0.7068	-0.71	-0.2449	-0.2743	-0.2701	-0.269
13	-0.6648	-0.7109	-0.7068	-0.71	-0.2449	-0.2743	-0.2701	-0.269
14	-0.3489	-0.3885	-0.3882	-0.391	-0.3042	-0.3341	-0.3305	-0.33
15	-1.2072	-1.2645	-1.2538	-1.25	-0.309	-0.3389	-0.3354	-0.335

Table 6 The Calibrated Results of Current Equality and Power Loss at point 5 , 6

Hour	PM(5)	PCI(5)	PCL(5)	Actual	PM(6)	PCI(6)	PCL(6)	Actual
1	0.1677	0.1969	0.1947	0.1921	0.1554	0.1835	0.1859	0.192
2	0.2018	0.2326	0.2298	0.2269	0.1892	0.2184	0.2204	0.227
3	0.3907	0.4302	0.4245	0.4195	0.3762	0.4112	0.4111	0.419
4	0.4827	0.5265	0.5193	0.5133	0.4673	0.5051	0.504	0.513
5	0.253	0.2862	0.2826	0.279	0.2398	0.2705	0.272	0.279
6	0.1847	0.2147	0.2122	0.2094	0.1722	0.2009	0.203	0.209
7	0.141	0.169	0.1672	0.1649	0.129	0.1563	0.1589	0.164
8	0.2743	0.3085	0.3045	0.3008	0.261	0.2924	0.2936	0.3
9	0.4348	0.4764	0.4699	0.4645	0.4199	0.4562	0.4557	0.464
10	0.4409	0.4827	0.4762	0.4708	0.426	0.4625	0.4619	0.47
11	0.502	0.5466	0.5392	0.533	0.4864	0.5248	0.5235	0.533
12	0.3276	0.3642	0.3595	0.3552	0.3138	0.3468	0.3474	0.355
13	0.3276	0.3642	0.3595	0.3552	0.3138	0.3468	0.3474	0.355
14	0.1713	0.2007	0.1984	0.1957	0.159	0.1873	0.1895	0.195
15	0.5962	0.6452	0.6362	0.6291	0.5797	0.6209	0.6187	0.629

Hour	QM(5)	QCI(5)	QCL(5)	Actual	QM(6)	QCI(6)	QCL(6)	Actual
1	0.1444	0.1687	0.1687	0.1637	0.1318	0.1659	0.1619	0.163
2	0.1367	0.1608	0.1607	0.1558	0.1239	0.1581	0.1539	0.155
3	0.1003	0.1234	0.1228	0.1183	0.087	0.1213	0.1168	0.118
4	0.0398	0.0612	0.0599	0.056	0.0257	0.0603	0.0552	0.056
5	0.1318	0.1558	0.1556	0.1508	0.119	0.1532	0.149	0.15
6	0.1949	0.2206	0.2213	0.2158	0.183	0.2169	0.2134	0.215
7	0.1083	0.1316	0.1311	0.1265	0.0951	0.1294	0.125	0.126
8	0.1362	0.1603	0.1602	0.1552	0.1234	0.1576	0.1534	0.155
9	0.1395	0.1637	0.1636	0.1587	0.1268	0.1609	0.1569	0.158
10	0.1356	0.1597	0.1596	0.1547	0.1229	0.1571	0.1529	0.154
11	0.1496	0.1741	0.1741	0.1691	0.137	0.1711	0.1671	0.169
12	0.1164	0.1399	0.1396	0.1349	0.1033	0.1376	0.1332	0.134
13	0.1164	0.1399	0.1396	0.1349	0.1033	0.1376	0.1332	0.134
14	0.1458	0.1701	0.1702	0.1652	0.1332	0.1673	0.1633	0.165
15	0.1482	0.1726	0.1727	0.1676	0.1356	0.1697	0.1657	0.167

Hour	VM(5)	VCI(5)	VCL(5)	Actual	VM(6)	VCI(6)	VCL(6)	Actual
1	0.952	0.9752	0.9752	0.97	0.9406	0.9748	0.9748	0.97
2	0.942	0.9659	0.966	0.96	0.9307	0.9655	0.9655	0.96
3	0.9319	0.956	0.9566	0.95	0.9208	0.9561	0.9562	0.95
4	0.957	0.9799	0.9799	0.975	0.9455	0.9795	0.9795	0.975
5	0.962	0.9845	0.9845	0.98	0.9505	0.9842	0.9842	0.98
6	0.9771	0.9986	0.9985	0.995	0.9653	0.9982	0.9981	0.995
7	0.9972	1.0173	1.0171	1.01	0.9851	1.017	1.0168	1.01
8	1.0022	1.0219	1.0217	1.02	0.9901	1.0217	1.0215	1.02
9	0.9369	0.9612	0.9613	0.955	0.9257	0.9607	0.9608	0.955
10	0.9269	0.9519	0.952	0.945	0.9158	0.9513	0.9515	0.945
11	0.9219	0.9472	0.9474	0.94	0.9109	0.9467	0.9468	0.94
12	0.952	0.9752	0.9752	0.97	0.9406	0.9748	0.9748	0.97
13	0.952	0.9752	0.9752	0.97	0.9406	0.9748	0.9748	0.97
14	0.962	0.9845	0.9845	0.98	0.9505	0.9842	0.9842	0.98
15	0.9219	0.9472	0.9474	0.94	0.9109	0.9467	0.9468	0.94

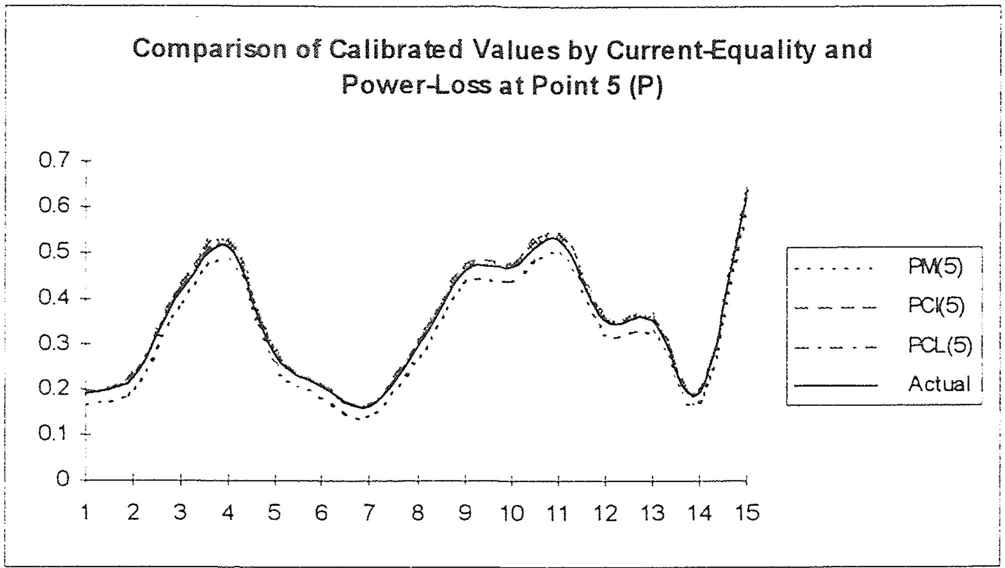


Figure 16 Comparison of Calibrated P by Current-Equality and Power-Loss at Point 5

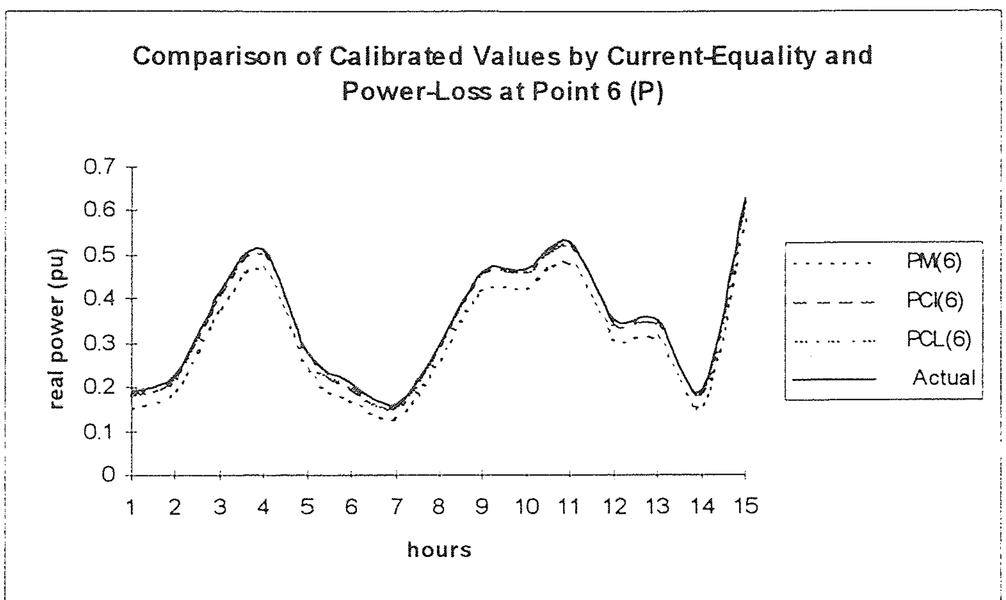


Figure 17 Comparison of Calibrated P by Current-Equality and Power Loss at Point 6

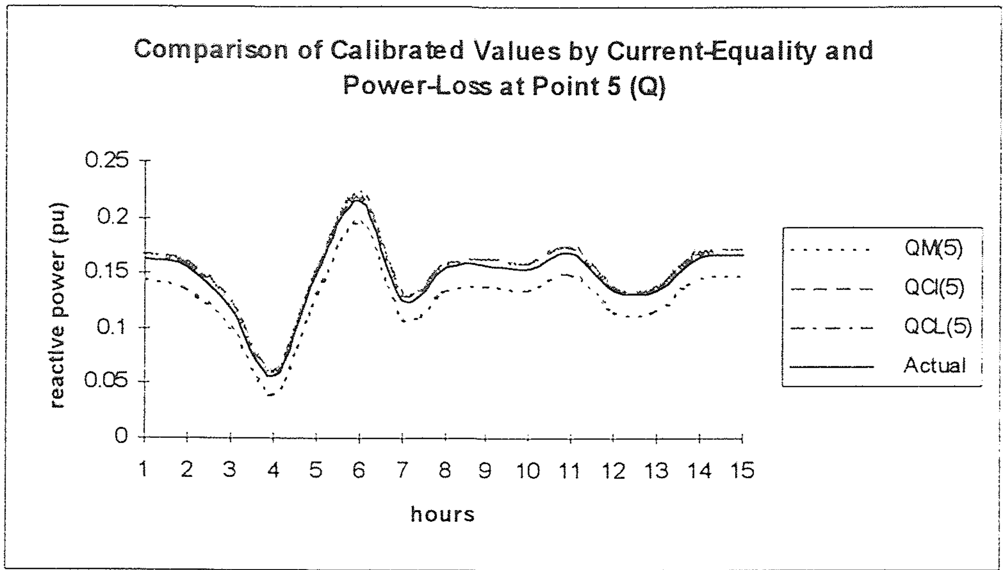


Figure 18 Comparison of Calibrated Q by Current-Equality and Power-Loss at Point 5

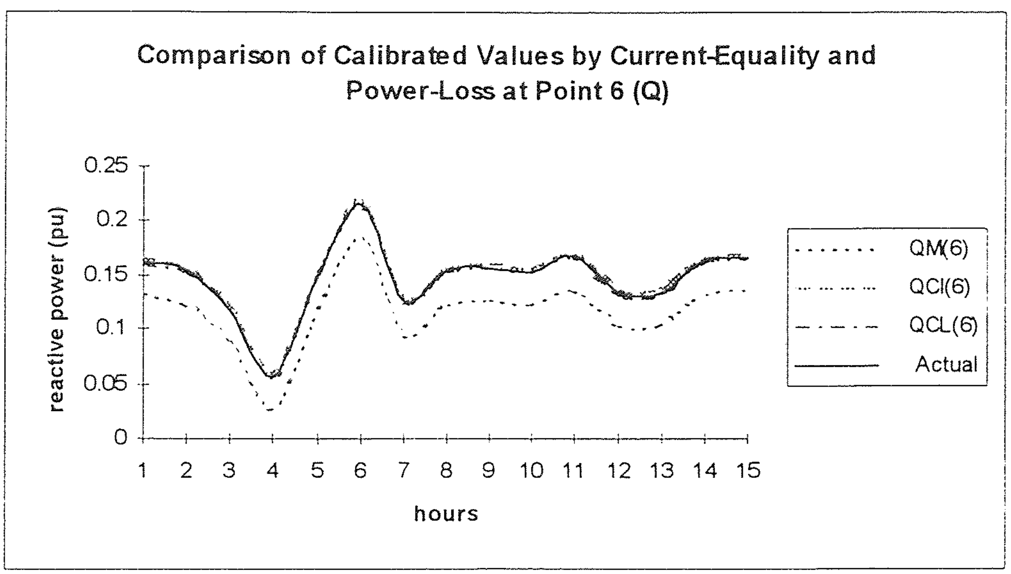


Figure 19 Comparison of Calibrated Q by Current -Equality and Power-Loss at Point 6

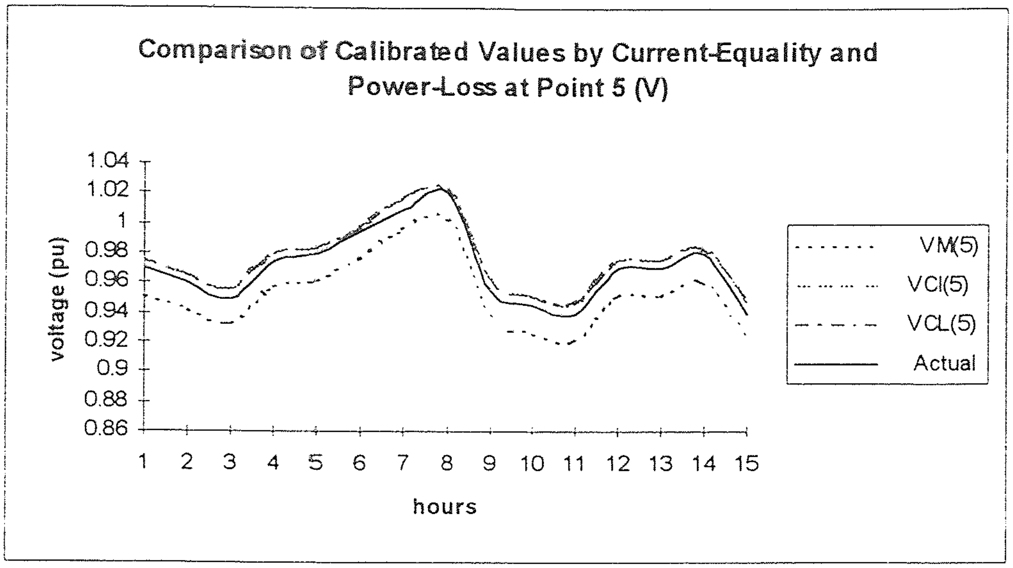


Figure 20 Comparison of Calibrated V by Current-Equality and Power-Loss at Point 5

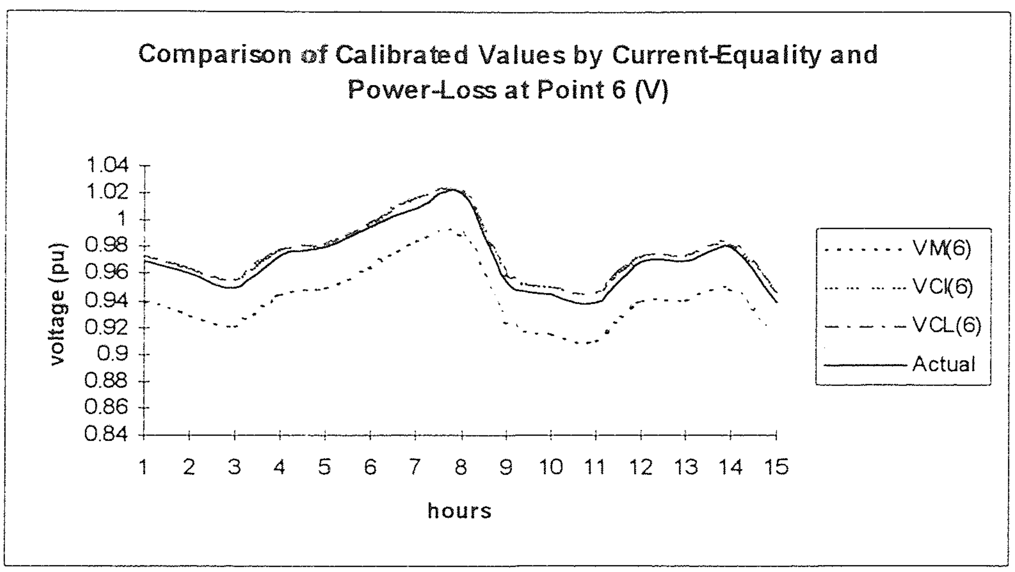


Figure 21 Comparison of Calibrated V by Current-Equality and Power-Loss at Point 6

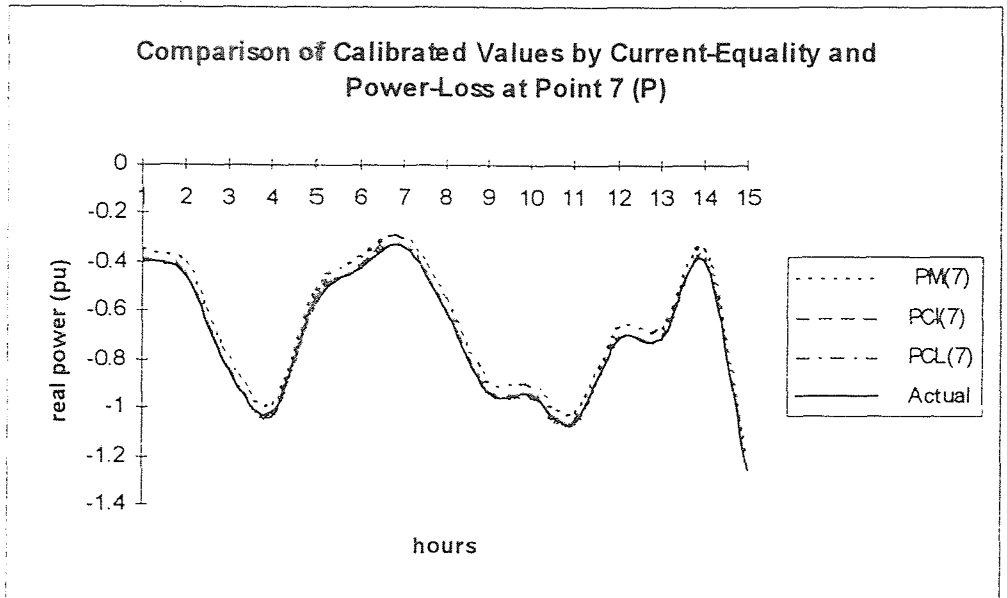


Figure 22 Comparison of Calibrated P by Current-Equality and Power-Loss at Point 7

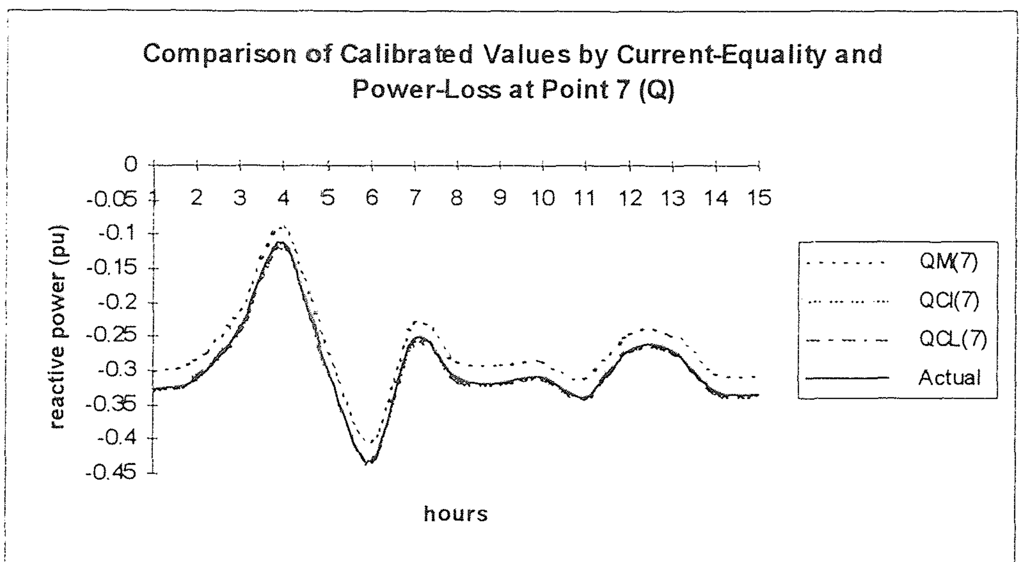


Figure 23 Comparison of Calibrated Q by Current-Equality and Power-Loss at Point 7

3.2 Complex System Case

3.2.1 Description of the Complex System

The proposed method was tested on 9-bus system (26 KV - 4 KV) which consists of a main generator at bus 1, 9 transformers, 9 lines and 3 reactors. The system also has four loads at buses 4, 5, 7 and 8, as well as capacitors or reactive power generators. The system is shown in Figure 24 which also shows 52 measurement points. These measurements include line real and reactive power flows and bus voltage. The power measurements consist of injection powers at some points, such as loads, and power flows at both ends of each line of this system.

3.2.2 Measurement Data

Load flow solutions were obtained according to a variety of load curve in order to generate hourly measurement data, like the simulation of the actual situations in power system. The results of load flow are referred to as actual values. Systematic errors of gain and zero offset were then introduced in all but a few points in order to generate the uncalibrated data. The few points which are left unchanged will be considered as reliable points. The modified data and the reliable point data become the measurement data of the system. In addition, random errors may be added to these measurements in order to simulate the hourly data of real-time measurements of EMS.

Assume a and b are the zero offset and gain coefficients respectively, P_c and P_m are the correct and measurement value.

$$P_m = \frac{P_c - a}{b} \qquad \text{if } P_c > 0$$

$$P_m = -\frac{|P_c| - a}{b} \qquad \text{if } P_c < 0$$

3.2.3 Selection of Reliable Points and Results of Calibration

Before embarking on the calibration of the test system, the location of reliable points are determined. The Remote Measurement Calibration (RMC) program is run in order to get the results of calibration based on that set of reliable points.

In this study, points 1, 2, 3, 4, 6, 15, 16, 18, 19, 27, 32, 33, 36, 38, 40 are the reliable points. The calibration results are close to the actual values. The algorithm is thus capable of minimizing the effects of systematic errors.

Reliable Points: 1, 2, 3, 4, 6, 15, 16, 18, 19, 27, 32, 33, 36, 38, 40

Calibrated Points: 5, 7, 8, 9, 10, 11, 12, 13, 14, 17, 20, 21, 22, 23, 24, 25, 26, 28, 29, 30, 31, 34, 35, 37, 39, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52

For the sake of brevity, we just report point 10, 11, 12, 13, 14, 17 at bus 2 . The results are shown in Table 7 and their plots are shown in Appendix C .

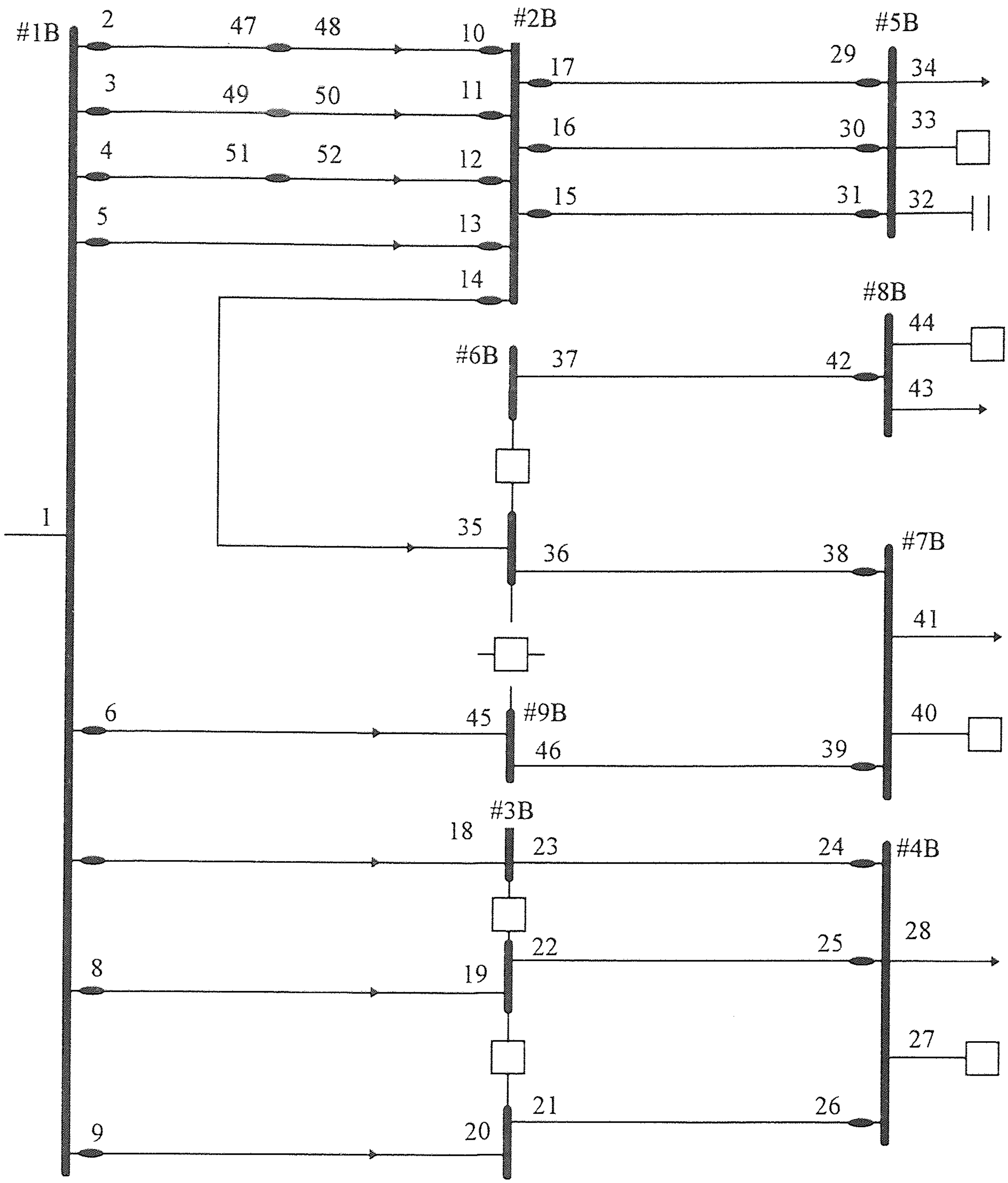


Figure 24 9-Bus Test System

Table 7 Calibrated Values of Some Points at Bus #2 of 9-Bus Test System

Hour	PM(10)	PC(10)	Actual	Hour	QM(10)	QC(10)	Actual
1	0.03029	0.03393	0.0339	1	-0.00775	-0.00793	-0.008
2	0.01461	0.01806	0.0179	2	-0.00922	-0.00946	-0.0095
3	0.02176	0.0253	0.0252	3	-0.00716	-0.00731	-0.0074
4	0.01873	0.02223	0.0221	4	-0.00696	-0.0071	-0.0072
5	0.02367	0.02719	0.0271	5	-0.00735	-0.00751	-0.0076
6	0.02824	0.03185	0.0318	6	-0.00765	-0.00782	-0.0079
7	0.0352	0.03889	0.0389	7	-0.00794	-0.00813	-0.0082
8	0.02716	0.03076	0.0307	8	-0.00745	-0.00762	-0.0077
9	0.076	0.08016	0.0805	9	0.02667	0.02808	-0.0273
10	0.0352	0.03889	0.0389	10	-0.00794	-0.00813	-0.0082

Hour	PM(11)	PC(11)	Actual	Hour	QM(11)	QC(11)	Actual
1	0.02735	0.03022	0.03	1	-0.00918	-0.00952	-0.0096
2	0.01314	0.01535	0.0155	2	-0.00947	-0.00984	-0.0099
3	0.01971	0.02222	0.0222	3	-0.00811	-0.00835	-0.0085
4	0.01696	0.01935	0.0194	4	-0.00762	-0.00782	-0.008
5	0.02137	0.02397	0.0239	5	-0.0084	-0.00867	-0.0088
6	0.02549	0.02827	0.0281	6	-0.00898	-0.00931	-0.0094
7	0.03166	0.03474	0.0344	7	-0.00976	-0.01016	-0.0102
8	0.02451	0.02725	0.0271	8	-0.00879	-0.0091	-0.0092
9	0.07088	0.07576	0.0744	9	0.0181	0.02043	0.0188
10	0.03166	0.03474	0.0344	10	-0.00976	-0.01016	-0.0102

Hour	PM(12)	PC(12)	Actual	Hour	QM(12)	QC(12)	Actual
1	0.02563	0.0298	0.0296	1	-0.00906	-0.00943	-0.0096
2	0.01175	0.01526	0.0153	2	-0.00936	-0.00974	-0.0099
3	0.01816	0.02197	0.0219	3	-0.00798	-0.00831	-0.0085
4	0.01553	0.01922	0.0192	4	-0.00759	-0.0079	-0.008
5	0.01981	0.0237	0.0236	5	-0.00828	-0.00862	-0.0088
6	0.02379	0.02787	0.0277	6	-0.00887	-0.00923	-0.0094
7	0.0299	0.03428	0.034	7	-0.00966	-0.01005	-0.0102
8	0.02816	0.02685	0.0267	8	-0.00867	-0.00903	-0.0092
9	0.06825	0.07446	0.0735	9	0.01793	0.01856	0.0188
10	0.0299	0.03428	0.034	10	-0.00966	-0.01005	-0.0102

Hour	PM(13)	PC(13)	Actual	Hour	QM(13)	QC(13)	Actual
1	0.04796	0.05221	0.0529	1	-0.03392	-0.03436	-0.035
2	0.02058	0.02391	0.0247	2	-0.02667	-0.02749	-0.0276
3	0.03388	0.03766	0.0384	3	-0.02765	-0.02841	-0.0286
4	0.02893	0.03254	0.0333	4	-0.02529	-0.02618	-0.0262
5	0.03689	0.04077	0.0415	5	-0.02912	-0.02981	-0.0301
6	0.04456	0.0487	0.0494	6	-0.03245	-0.00332	-0.0335
7	0.05602	0.06054	0.0612	7	-0.03745	-0.03851	-0.0386
8	0.04272	0.04679	0.0475	8	-0.03157	-0.03213	-0.0326
9	0.1468	0.15435	0.1547	9	-0.00343	-0.00385	-0.0039
10	0.05602	0.06054	0.0612	10	-0.03745	-0.03851	-0.0386

Table 7 (Continued)

Hour	PM(14)	PC(14)	Actual	Hour	QM(14)	QC(14)	Actual
1	-0.0304	-0.03232	-0.0317	1	0.02513	0.02555	0.0257
2	-0.01713	-0.01827	-0.0183	2	0.0194	0.01963	0.0198
3	-0.02158	-0.02298	-0.0228	3	0.02231	0.02264	0.0228
4	-0.01792	-0.01911	-0.0191	4	0.021242	0.02154	0.0218
5	-0.02594	-0.0276	-0.0272	5	0.02348	0.02384	0.024
6	-0.0305	-0.03242	-0.0318	6	0.02503	0.02545	0.0256
7	-0.03436	-0.03651	-0.0357	7	0.02658	0.02705	0.0272
8	-0.02584	-0.02749	-0.0271	8	0.02386	0.02424	0.0244
9	-0.08545	-0.09062	-0.0873	9	-0.00231	-0.0028	-0.0027
10	-0.03436	-0.03651	-0.0357	10	0.02658	0.02705	0.0272

Hour	PM(17)	PC(17)	Actual	Hour	QM(17)	QC(17)	Actual
1	-0.03824	-0.04026	-0.0411	1	0.003932	0.00395	0.004
2	-0.01755	-0.01935	-0.02	2	0.004126	0.00418	0.0042
3	-0.02784	-0.02975	-0.0305	3	0.001893	0.00187	0.0019
4	-0.02392	-0.02579	-0.0265	4	0.009272	0.00949	0.0096
5	-0.02922	-0.03114	-0.0319	5	0.002282	0.00237	0.0024
6	-0.03392	-0.0359	-0.0367	6	0.003447	0.00367	0.0037
7	-0.04451	-0.0466	-0.0475	7	0.005194	0.00548	0.0055
8	-0.0348	-0.03679	-0.0376	8	0.003252	0.00346	0.0035
9	-0.10039	-0.1031	-0.01045	9	-0.01985	-0.02058	-0.0206
10	-0.04451	-0.0466	-0.0475	10	0.005194	0.00548	0.0055

Hour	VM(10)	VC(10)	VM(11)	VC(11)	VM(12)	VC(12)	Actual
1	1.00196	1.03815	1.02211	1.03683	1.00891	1.03731	1.039
2	1.00294	1.03912	1.02312	1.03767	1.0099	1.03828	1.04
3	1.00294	1.03912	1.02312	1.03767	1.0099	1.03828	1.04
4	1.00294	1.03912	1.02312	1.03767	1.0099	1.03828	1.04
5	1.00196	1.03815	1.02211	1.03683	1.00891	1.03731	1.039
6	1.00196	1.03815	1.02211	1.03683	1.00891	1.03731	1.039
7	1.00196	1.03815	1.02211	1.03683	1.00891	1.03731	1.039
8	1.00196	1.03815	1.02211	1.03683	1.00891	1.03731	1.039
9	0.99216	1.02842	1.01206	1.02842	0.99901	1.02764	1.029
10	1.00196	1.03815	1.02211	1.03683	1.00891	1.03731	1.039

Hour	VM(13)	VC(13)	VM(14)	VC(14)	VM(17)	VC(17)	Actual
1	1.00594	1.03808	0.99414	1.03806	1.02211	1.03806	1.039
2	1.00693	1.03904	0.99512	1.03902	1.02311	1.03902	1.04
3	1.00693	1.03904	0.99512	1.03902	1.02311	1.03902	1.04
4	1.00693	1.03904	0.99512	1.03902	1.02311	1.03902	1.04
5	1.00594	1.03808	0.99414	1.03806	1.02211	1.03806	1.039
6	1.00594	1.03808	0.99414	1.03806	1.02211	1.03806	1.039
7	1.00594	1.03808	0.99414	1.03806	1.02211	1.03806	1.039
8	1.00594	1.03808	0.99414	1.03806	1.02211	1.03806	1.039
9	0.99604	1.02847	0.98439	1.02849	1.01206	1.02849	1.029
10	1.00594	1.03808	0.99414	1.03806	1.02211	1.03806	1.039

CHAPTER 4

DISCUSSION

In the previous chapters, we have introduced the methodology of RMC and conducted case study of the simple and complex system. The calibration improved significantly the measured values. The method is noted for the following:

a. Only a few reliable points in the power system need frequent field calibration. Those are the reliable points which essentially establish power and voltage reference. Soft calibration of the rest of the points results in values that are very close to the actual values.

b. Power Balance constraint is used to do calibration at one bus with at least one reliable point.

c. Current equality constraint plus voltage drop constraint is used to propagate the calibration to other buses which are connected to the reliable or calibrated points.

d. Using the power loss constraint plus voltage drop constraint to do (c) seems to be slightly better than using current equality plus voltage drop.

2. Future work should focus on the following:

a. It was assumed that each measurement point has real power, reactive power, and voltage measurements. In a real life situation, some measurement points may only have real power, reactive power and no voltage measurement, or some other situations.

b. The locations of reliable points play an important part in the soft calibration. A topological study would enhance the proposed technique by providing the system planner with some guidance in the selection of reliable points.

CHAPTER 5

CONCLUSION

The calibration method described has the following advantages:

a. it remotely calibrates the voltage, real and reactive power measurements

b. it permits the adjustments of measurement scales of SCADA at the control center on an economic scale.

c. it does not require extensive field calibration, a procedure which invariably introduces its own errors and which sometimes interferes with normal operation of the power system.

d. it significantly reduces the expenditures associated with the field calibrations of several thousand instruments.

e. it directs the field technician, by exception, to inspect only those instruments which are found to be widely out-of-range.

APPENDIX A

PROGRAM OF SIMULATING THE MEASUREMENT DATA

```
**************************************************
*                  PROGRAM NAME  generate_meas.for
*                                -----------------
**************************************************
* the program is used to generate measurement  data for RMC
*     math model:  Pm=(Pc-a)/b  and/or Pm=-(| Pc| - a )/b
**************************************************
        REAL PM(10,52),QM(10,52),VM(10,52)
        REAL PA(10,52),QA(10,52),VA(10,12)
         REAL X(3,104)
C--------------------------------------------------
        OPEN(UNIT=12, NAME='actual.dat', TYPE='OLD')
        OPEN(UNIT=6, NAME='system2.dat',TYPE='NEW')
        READ(12,*)((PA(I,J),J=1,52),I=1,10)
        READ(12,*)((QA(I,J),J=1,52),I=1,10)
        READ(12,*)((VA(I,J),J=1,12),I=1,10)
C---------------------------------------------
        READ(12,*)((X(I,J),J=1,104),I=1,3)
C-----------------------------------------------
        DO 100 I=1,10
          DO 90 J=1,52
           IF(PA(I,J).GE.0) THEN
                PM(I,J)=(PA(I,J)-X(2,2*J-1)/10)/X(2,2*J)
           ELSE
                PM(I,J)=-(ABS(PA(I,J))-X(2,2*J-1)/10)/X(2,2*J)
           END IF
           IF(QA(I,J).GE.0) THEN
           QM(I,J)=(QA(I,J)-X(3,2*J-1)/100)/X(3,2*J)
           ELSE
                QM(I,J)=-(ABS(QA(I,J))-X(3,2*J-1)/100)/X(3,2*J)
           END IF
 90       CONTINUE
 100    CONTINUE
C-------------------------------------------------
        DO 200 I=1,10
        WRITE(6,*) (PM(I,J),J=1,52)
 200    CONTINUE
        DO 210 I=1,10
        WRITE(6,*) (QM(I,J),J=1,52)
 210    CONTINUE
        DO 300 I=1,10
```

```
      DO 310 J=1,9
      VM(I,J)=(VA(I,1)-X(1,2*J-1)/10)/X(1,2*J)
310   CONTINUE
      DO 320 J=10,17
      VM(I,J)=(VA(I,2)-X(1,2*J-1)/10)/X(1,2*J)
320   CONTINUE
      VM(I,18)=(VA(I,3)-X(1,35)/10)/X(1,36)
      VM(I,23)=(VA(I,3)-X(1,45)/10)/X(1,46)
      VM(I,19)=(VA(I,11)-X(1,37)/10)/X(1,38)
      VM(I,22)=(VA(I,11)-X(1,43)/10)/X(1,44)
      VM(I,20)=(VA(I,12)-X(1,39)/10)/X(1,40)
      VM(I,21)=(VA(I,12)-X(1,41)/10)/X(1,42)
      VM(I,35)=(VA(I,10)-X(1,69)/10)/X(1,70)
      VM(I,36)=(VA(I,10)-X(1,71)/10)/X(1,72)
      VM(I,37)=(VA(I,6)-X(1,73)/10)/X(1,74)
      DO 330 J=24,28
      VM(I,J)=(VA(I,4)-X(1,2*J-1)/10)/X(1,2*J)
330   CONTINUE
      DO 340 J=29,34
      VM(I,J)=(VA(I,5)-X(1,2*J-1)/10)/X(1,2*J)
340   CONTINUE
      DO 350 J=38,41
      VM(I,J)=(VA(I,7)-X(1,2*J-1)/10)/X(1,2*J)
350   CONTINUE
      DO 360 J=42,44
      VM(I,J)=(VA(I,8)-X(1,2*J-1)/10)/X(1,2*J)
360   CONTINUE
      DO 370 J=45,46
      VM(I,J)=(VA(I,9)-X(1,2*J-1)/10)/X(1,2*J)
370   CONTINUE
      VM(I,47)=(VA(I,1)-X(1,93)/10)/X(1,94)
      VM(I,49)=(VA(I,1)-X(1,97)/10)/X(1,98)
      VM(I,51)=(VA(I,1)-X(1,101)/10)/X(1,102)
      VM(I,48)=(VA(I,2)-X(1,95)/10)/X(1,96)
      VM(I,50)=(VA(I,2)-X(1,99)/10)/X(1,100)
      VM(I,52)=(VA(I,2)-X(1,101)/10)/X(1,102)
300   CONTINUE
      DO 220 I=1,10
      WRITE(6,*) (VM(I,J),J=1,52)
220   CONTINUE
      CLOSE (UNIT=6)
      CLOSE (UNIT=12)
      END
```

APPENDIX B

PROGRAM OF REMOTE MEASUREMENT CALIBRATION (RMC)

```
*******************************************************
* This Program is for Remote Measurement Calibration (RMC)
*  Program Name: abrmc.for     Output Name: system1.outoutput
*******************************************************
C ------------PART 1 : THE SYSTEM DATA DECLARATION ----------
     COMMON/DATA1/ P(M, NM),Q(M,NM),V(M,NM)
     COMMON/DATA2/ NLM,M,NTL,NB
     COMMON/DATA3/ A(3,NM),B(3,NM)
     COMMON/DATA4/ KF
     COMMON/DATA5/ ILNST(NTL),ILNED(NTL),MBST(NB),MBED(NB),NS(5)
     COMMON/DATA6/ PC(M,NM),QC(M,NM),VC(M,NM),VB(M,NB)
     COMMON/DATA7/ NMP, JJ
C ---------------------------------------------------------------
     PARAMETER ( M=15, NM=7, NB=2, NTL=5)
     REAL X(15),XGUESS(15),XSCALE(15),XLB(15),XUB(15),F(120),FV(120),
    &    FSCALE(120),FJ(120,15),RP(7)
     INTEGER RA,K1,IDSYS,ND,M,N,NF,NLINE,NT,NSYS,KF,
    &       IP(6),NNS(3),ND2,ND3
     EXTERNAL UNLSF,U4LSF,FUN,FUP,FUNI
     OPEN (UNIT=6, NAME='system1.out', TYPE='NEW')
     OPEN (UNIT=2, NAME='system1.dat', TYPE='OLD')
CC --------Begin to Read System Measurement Data ------------
     DATA ILNST /0,0,3,4,7/
     DATA ILNED/1,2,5,6,0/
     DATA MBST/1,5/,MBED/4,7/
        WRITE(6,500)
        WRITE(6,511) ILNED(1),ILNST(5)
      DO 30 I=1,M
      READ(2,*) (P(I,J), J=1,NM)   ! read real power measurements
        WRITE(6,512) (P(I,J),J=1,NM) ! write real power measurements
 30    CONTINUE
        WRITE(6,500)
        WRITE(6,513) ILNED(1),ILNST(5)
      DO 31 I=1,M
      READ(2,*) (Q(I,J),J=1,NM)    ! read reactive power measurements
        WRITE(6,512) (Q(I,J),J=1,NM) ! write reactive power measurements
 31    CONTINUE
        WRITE(6,500)
        WRITE(6,510) ILNED(1),ILNST(5)
      DO 32 I=1,M
      READ(2,*) (V(I,J),J=1,NM)    ! read voltage  measurements
```

```
      WRITE(6,512) (V(I,J),J=1,NM) ! write voltage measurements
  32   CONTINUE
      DO 36 I=1,M
      DO 36 J=1,NM
      PC(I,J)=0.0
        QC(I,J)=0.0
        VC(I,J)=0.0
  36   CONTINUE
        DO 37 I=1,M
        DO 37 J=1,2
        PC(I,J)=P(I,J)     ! reliable points 1,2, PC=PM
        QC(I,J)=Q(I,J)      ! reliable points 1,2, QC=QM
        VC(I,J)=V(I,J)      ! reliable points 1,2, VC=VM
  37   CONTINUE
C    Select actual points to calibrate
C-----------------------------------------
                NMP=0
                NNZ=0
      DO 660 JJ=1,2
        NMP=0
      NNZ=0
        SUMV=0.0
        DO 77 J=MBST(JJ),MBED(JJ)
        IF (VC(1,J).NE.0.0) GO TO 707
        NMP=NMP+1
        NS(NMP)=J
        GO TO 77
 707   NNZ=NNZ+1
      NNS(NNZ)=J
  77   CONTINUE
        DO 78 I=1,M
        DO 79 J=1,NNZ
  79   SUMV=SUMV+VC(I,NNS(J))
        VB(I,JJ)=SUMV/NNZ
        SUMV=0.0
  78   CONTINUE
***********************************************************************
*  PART2:  The Measurement Model Is as follows:
*  -------        VC(I)=a1(I) + b1(I)*VM(I)
*                 PC(I)=a2(I) + b2(I)*PM(I)
*                 QC(I)=a3(I) + b3(I)*QM(I)
*  Using Power Balance Constraints , Voltage Drop Constraints And Current Equality
*  Constraints To Minimization The Function By Least Square Method(IMSL UNLSF),  *
And Then We Got Coefficients and can Calibrate P, Q, V.
***********************************************************************
```

```
      WRITE(6,500)
      WRITE(6,502) MBST(JJ), MBED(JJ)
      WRITE(6,515) (J,J=MBST(JJ),MBED(JJ))  ! NBS(JJ)/MBST(JJ)  Mar 10,96.
    DO 75 I=1,M
    DO 76 J=1,NMP
 76  VC(I,NS(J))=VB(I,JJ)
      WRITE(6,980) I,(VC(I,J),J=MBST(JJ),MBED(JJ))
980   FORMAT(1X,I3,3X,4(F7.4,3X))
 75  CONTINUE
      WRITE(6,500)
 61  WRITE(6,501) JJ
      ND=2*NMP
      MSC=M*(NMP+1)
      IDSYS=1    ! use power balance constraints for one bus
      GO TO  206
206    DO 70 KF=1,2
210    CALL SOLVE (MSC,IDSYS,KF,ND,X) ! to calibrate P,Q measurements
C
      DO 208 I=1,NMP
      A(KF+1,NS(I))=X(2*I-1)
      B(KF+1,NS(I))=X(2*I)
208   CONTINUE
C ************************************************
      IF (KF.EQ.2) GO TO 303
      WRITE(6,503) MBST(JJ),MBED(JJ)
      WRITE(6,515) (J,J=MBST(JJ),MBED(JJ))
      DO 300 I=1,M
      DO 310 J=1,NMP
      PC(I,NS(J))=A(2,NS(J))+B(2,NS(J))*P(I,NS(J))
310   CONTINUE
      WRITE(6,981) I,(PC(I,J),J=MBST(JJ),MBED(JJ))
981   FORMAT(1X,I3,3X,4(F7.4,3X))
300    CONTINUE
      WRITE(6,500)
      GO TO 70
303   WRITE(6,500)
      WRITE(6,504) MBST(JJ), MBED(JJ)
      WRITE(6,515) (J, J=MBST(JJ), MBED(JJ))
      DO 301 I=1,M
      DO 302 J=1,NMP
      QC(I,NS(J))=A(3,NS(J))+B(3,NS(J))*Q(I,NS(J))
302   CONTINUE
301    WRITE(6,982) I,(QC(I,J),J=MBST(JJ),MBED(JJ))
982   FORMAT(1X,I3,3X,4(F7.4,3X))
      WRITE(6,500)
```

```
 70   CONTINUE
      WRITE(6,519)
      WRITE(6,997) (A(1,J),B(1,J),J=MBST(JJ),MBED(JJ))
      WRITE(6,500)
      WRITE(6,998) (A(2,J),B(2,J),J=MBST(JJ),MBED(JJ))
      WRITE(6,500)
      WRITE(6,999) (A(3,J),B(3,J),J=MBST(JJ),MBED(JJ))
 997  FORMAT(3X,'Coefficients of V',3X,F7.4,5X,F7.4)
 998  FORMAT(3X,'Coefficients of P',3X,F7.4,5X,F7.4)
 999  FORMAT(3X,'Coefficients of Q',3X,F7.4,5X,F7.4)
C ---------------------------------------------------
      IF (JJ.EQ.NB) GO TO 660
      WRITE(6,500)
      IDSYS=2   ! use current equality and voltage drop between 2 buses
      DO 700 I=1,NTL
      IF((ILNST(I).EQ.0).OR.(ILNED(I).EQ.0)) GO TO 700
      ND=6
      MSC=2*M
      N1=ILNST(I)
      N2=ILNED(I)
      KF=I
      CALL SOLVE (MSC,IDSYS,KF,ND,X) ! to calibrate the P,Q,V
      DO 701 I1=1,3
      A(I1,ILNED(KF))=X(2*I1-1)
 701  B(I1,ILNED(KF))=X(2*I1)
      DO 702 J=1,M
      VC(J,ILNED(KF))=A(1,ILNED(KF))+B(1,ILNED(KF))*V(J,ILNED(KF))
      PC(J,ILNED(KF))=A(2,ILNED(KF))+B(2,ILNED(KF))*P(J,ILNED(KF))
      QC(J,ILNED(KF))=A(3,ILNED(KF))+B(3,ILNED(KF))*Q(J,ILNED(KF))
 702  CONTINUE
      WRITE(6,500)
      WRITE(6,990) ILNED(KF)
 990  FORMAT(1X,'The calibrated value of voltage at point',I3)
      DO 705 J=1,M
 705  WRITE(6,880) J,VC(J,ILNED(KF))
 880  FORMAT(3X,I3,4X,F7.4)
      WRITE(6,500)
      WRITE(6,991) ILNED(KF)
 991  FORMAT(1X,'The calibrated value of real power at point',I3)
      DO 703 J=1,M
 703  WRITE(6,881) J,PC(J,ILNED(KF))
 881  FORMAT(3X,I3,4X,F7.4)
      WRITE(6,500)
      WRITE(6,992) ILNED(KF)
 992  FORMAT(1X,'The calibrated value of reactive power at point',I3)
```

```
      DO 704 J=1,M
  704 WRITE(6,882) J,QC(J,ILNED(KF))
  882 FORMAT(3X,I3,4X,F7.4)
  700 CONTINUE
  660 CONTINUE
  500 FORMAT (2X/)
  512 FORMAT (7(2X,F7.4))
  501 FORMAT (3X,20('='),I3,20('=')/)
  502 FORMAT (1X,'-----The calibrated voltage(V) of',2(I3),'-----')
  503 FORMAT (1X,'-----The calibrated real power(P) of',2(I3),'-----')
  504 FORMAT (1X,'---The calibrated reactive power(Q) of',2(I3),'--')
  510 FORMAT (1X,'-----The measured voltage(V) of',2(I3),'-----')
  511 FORMAT (1X,'-----The measure real power(P) of',2(I3),'-----')
  513 FORMAT (1X,'----The measured reactive power(Q) of',2(I3),'--')
  515 FORMAT (8X,4(I3,8X)/,2X,55('-'))
  519 FORMAT (1X,'------The Coefficients of A and B------')
      END
C
*******************************************************************
* PART 3:
* ---------
*  The Subroutine(SOLVE) Input=IDSYS And Output(X) or a and b
*
*******************************************************************

      SUBROUTINE SOLVE (MSC,IDSYS,KF,ND,X)

      COMMON/DATA1/ P(24,7), Q(24,7), V(24,7)
      COMMON/DATA2/ NM,M,NTL,NB
      COMMON/DATA3/ A(3,7), B(3,7)
C     COMMON/DATA4/ KF
      COMMON/DATA5/ILNST(5),ILNED(5),MBST(2),MBED(2),NS(2)
      REAL X(15),XGUESS(15),XSCALE(15),FJ(120,15),FV(120),FSCALE(120)
      REAL XLB(15),XUB(15),RP(7)
      EXTERNAL UNLSF,U4LSF,FUN,FUP,FUNI
      INTEGER  M,N,LDF,IP(6),ND,ND1,KF,IDSYS,ND2,ND3,IPT
      LDF=MSC
C ***********************************************************
      ND1=ND/2
      DO 120 I=1,ND1
      XGUESS(2*I-1)=0.0
      XGUESS(2*I)=1.0
  120 CONTINUE
C     WRITE(6,515) (XGUESS(I),I=1,ND)
      DO 100 I=1,ND
```

```
 100   XSCALE(I)=1.0
       DO 110 I=1,MSC
 110   FSCALE(I)=1.0
       IP(1)=0  ! modified on April 1,96
       IF (IDSYS.EQ.1) GO TO 150
       IF (IDSYS.EQ.2) GO TO 160
C -----------------------------------------------------
       WRITE(6,500)
CALL  UNLSF(FUN,MSC,ND,XGUESS,XSCALE,FSCALE,IP,RP,X,FV,FJ,LDF)
       WRITE(6,514)
       WRITE(6,515) (X(I), I=1,ND)
       WRITE(6,500)
       SUMV=0.0
       DO 131 I=1,M
 131   SUMV=SUMV+FV(I)**2
       ERROR=SQRT(SUMV)
C -----------------------------------------------------
150   WRITE(6,500)
       CALL
UNLSF(FUP,MSC,ND,XGUESS,XSCALE,FSCALE,IP,RP,X,FV,FJ,LDF)
       SUMV=0.0
       WRITE(6,500)
       GO TO 140
C -----------------------------------------------------
 160   ITP=0
       NG=ND/2
       RPM=20
C      IP(1)=0
  10   CALL U4LSF (IP,RP)
       RP(1)=RPM*RP(1)
       RP(4)=RPM*RP(4)
CALL UNLSF(FUNI,MSC,ND,XGUESS,XSCALE,FSCALE,IP,RP,X,FV,FJ,LDF)
       SUMV=0.0
       ERROR=SQRT(SUMV)
       DELMAX=0.0
       DO 11 I=1,ND
       DELTAX=X(I)-XGUESS(I)
       IF (DELTAX .LT. 0.0) DELTAX=-DELTAX
  11   IF (DELTAX. GT. DELMAX) DELMAX=DELTAX
       IF ((DELMAX. LT. 0.0000006).AND.(RP(1).LE.0.125)) GO TO 12
     DO 13 I=1,ND
  13   XGUESS(I)=X(I)
       IF (RP(1) .GT. 2.0) RPM=RPM/5.0
       IF (RP(1) .LE. 2.0) RPM=RPM/2.0
       GO TO 10
```

```
 140  WRITE (6,500)
 500  FORMAT(3X,/)
 515  FORMAT (12(2X,F7.4))
 514  FORMAT (4X,'THE A(I,J) AND B(1,J) OF THE VOLTAGES'/)
 517  FORMAT (4X,'THE A(2,3,J) AND B(2,3,J) OF P AND Q POWER'/)
12    RETURN
      END
****************************************************************
* PART 4:
* -------
* The Subroutines That Define Power Balance, Voltage Drop  and Current
* Equality Constraints and Objective Functions.
****************************************************************
      SUBROUTINE FUN (MSC,ND,X,F)
C      ****************************
      INTEGER M,ND
      COMMON/DATA1/P(24,7),Q(24,7),V(24,7)
      COMMON/DATA2/ NLINE,M,NL,IBST,IBED
      COMMON/DATA4/ KF
      REAL X(15),F(120)
C ---------------------------------------------
      WRITE(6,*) NL,IBST,IBED
      M=15
      DO 80 J=1,M
      I1=IBST+2
      DO 81 I=1,2
      F(J+(I-1)*M)= X(2*I-1) + X(2*I)*V(J,I1) - V(J,IBST)
      I1=I1+1
 81   CONTINUE
      I1=IBST+2
      DO 85 I=1,2
      F(J+M*(NL-3+I))=-X(2*I)*V(J,I1)+V(J,I1)
 85   I1=1+I1
 80   CONTINUE
C     WRITE(6,*) (X(I),I=1,ND),ND
      RETURN
      END
CC ****************************************************************
      SUBROUTINE FUP (MSC,ND,X,F)
C      ******************************
      INTEGER M,ND
      COMMON/DATA1/ P(24,7),Q(24,7),V(24,7)
      COMMON/DATA2/ NM,M,NTL,NB
      COMMON/DATA4/ KF
      COMMON/DATA6/PC(24,7),QC(24,7),VC(24,7),VB(2)
```

```
      COMMON/DATA7/NMP,JJ
      COMMON/DATA5/ ILNST(5),ILNED(5),MBST(2),MBED(2),NS(5)
      REAL X(10),F(120)
C ----------------------------------------------------------
      SUM=0.0
      SUM1=0.0
      IF (KF.EQ.2) GO TO 91
      DO 90 I=1,M
      DO 92 J=1,NMP
      F(I+(J-1)*M)=X(2*J-1)+X(2*J)*P(I,NS(J))-P(I,NS(J))
      SUM1=SUM1+X(2*J-1)+X(2*J)*P(I,NS(J))
 92   CONTINUE
     DO 93 J=MBST(JJ),MBED(JJ)
      DO 94 J1=1,NMP
      IF (J.EQ.NS(J1)) GO TO 93
 94   CONTINUE
     SUM=SUM+PC(I,J)
 93   CONTINUE
     F(I+(NMP*M)) = (SUM+SUM1)*(MBED(JJ)-MBST(JJ)+1)
 90   CONTINUE
     GO TO 98
 91   DO 95 I=1,M
     SUM1=0.0
      SUM=0.0
     DO 96 J=1,NMP
      F(I+(J-1)*M)=X(2*J-1)+X(2*J)*Q(I,NS(J))-Q(I,NS(J))
      SUM1=SUM1+X(2*J-1)+X(2*J)*Q(I,NS(J))
 96   CONTINUE
      DO 651 J=MBST(JJ),MBED(JJ)
      DO 97  J1=1,NMP
      IF (J .EQ. NS(J1)) GO TO 651
 97   CONTINUE
      SUM=SUM+QC(I,J)
 651  CONTINUE
     F(I+(NMP*M))=(SUM+SUM1)*(MBED(JJ)-MBST(JJ)+1)
 95   CONTINUE
      SUM1=0.0
      SUM=0.0
 98   RETURN
     END
CC*****************************************************
      SUBROUTINE FUNI (MSC,ND,X,F)
C       ****************************
      INTEGER M,ND
      COMMON/DATA1/ P(24,7),Q(24,7),V(24,7)
```

```
      COMMON/DATA6/PC(24,7),QC(24,7),VC(24,7),VB(24,2)
      COMMON/DATA2/ NM,M,NTL,NB
      COMMON/DATA4/ KF
      COMMON/DATA7/ NMP,JJ
      COMMON/DATA5/ILNST(5),ILNED(5),MBST(2),MBED(2),NS(2)
      REAL X(15),F(120),FS,FE,FS1,FE1,XLB(15),XUB(15)
C -----------------------------------------------------
      DO 180 J=1,M
      FE1=X(3) + X(4)*P(J,ILNED(KF))
      FE2=X(5) + X(6)*Q(J,ILNED(KF))
      FEV=X(1)+X(2)*V(J,ILNED(KF))
      FS1=PC(J,ILNST(KF))
      FS2=QC(J,ILNST(KF))
      F1=(FS1**2+FS2**2)/VB(J,JJ)**2
      F2=(FE1**2+FE2**2)/(X(1)+X(2)*V(J,ILNED(KF)))**2
      FI1=SQRT((FS1**2+FS2**2)/VB(J,JJ)**2)
      FI2=SQRT((FE1**2+FE2**2)/(X(1)+X(2)*V(J,ILNED(KF)))**2)
      DELTP=ABS(ABS(FS1)-ABS(FE1))
      DELTQ=ABS(ABS(FS2)-ABS(FE2))
      F(J)=(F1+F2)*0.115-2*(DELTP+DELTQ)
      F(J+M)=FI1-FI2
      F5=Q(J,ILNED(KF))/(SQRT(P(J,ILNED(KF))**2+Q(J,ILNED(KF))**2))
      F61=ABS(FS1*P(J,ILNED(KF)))+ABS(FS2*Q(J,ILNED(KF)))
      F62=SQRT(FS1**2+FS2**2)*SQRT(P(J,ILNED(KF))**2+Q(J,ILNED(KF))**2)
      F6=F61/F62
      F(J+M+M)=FEV-VC(J,ILNST(KF))*F6+0.10111*FI1*F5
  180 CONTINUE
      RETURN
      END
```

APPENDIX C

PLOTS OF CALIBRATED AND MEASURED VALUES AT BUS 2

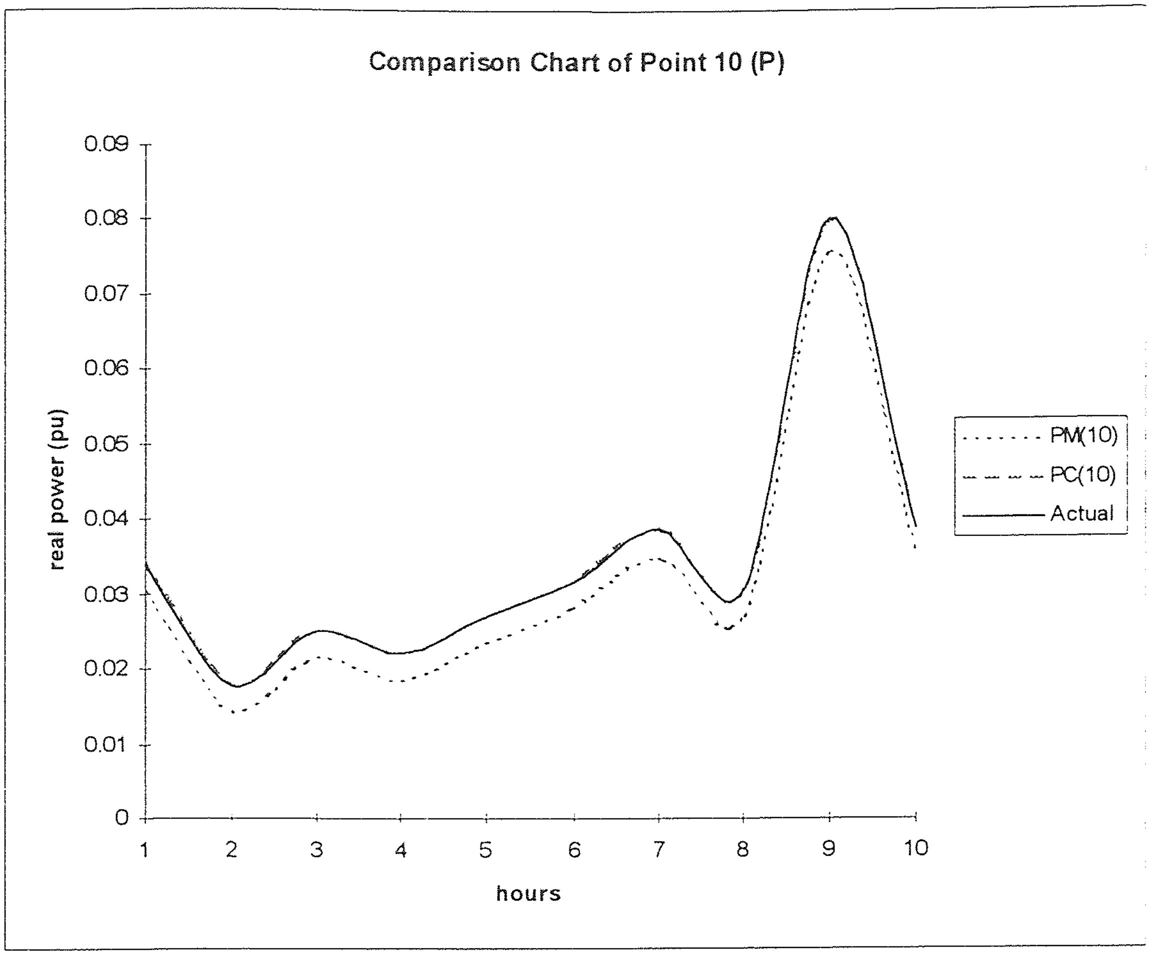


Figure 25 Comparison of Measured, Calibrated and Actual P at Point 10

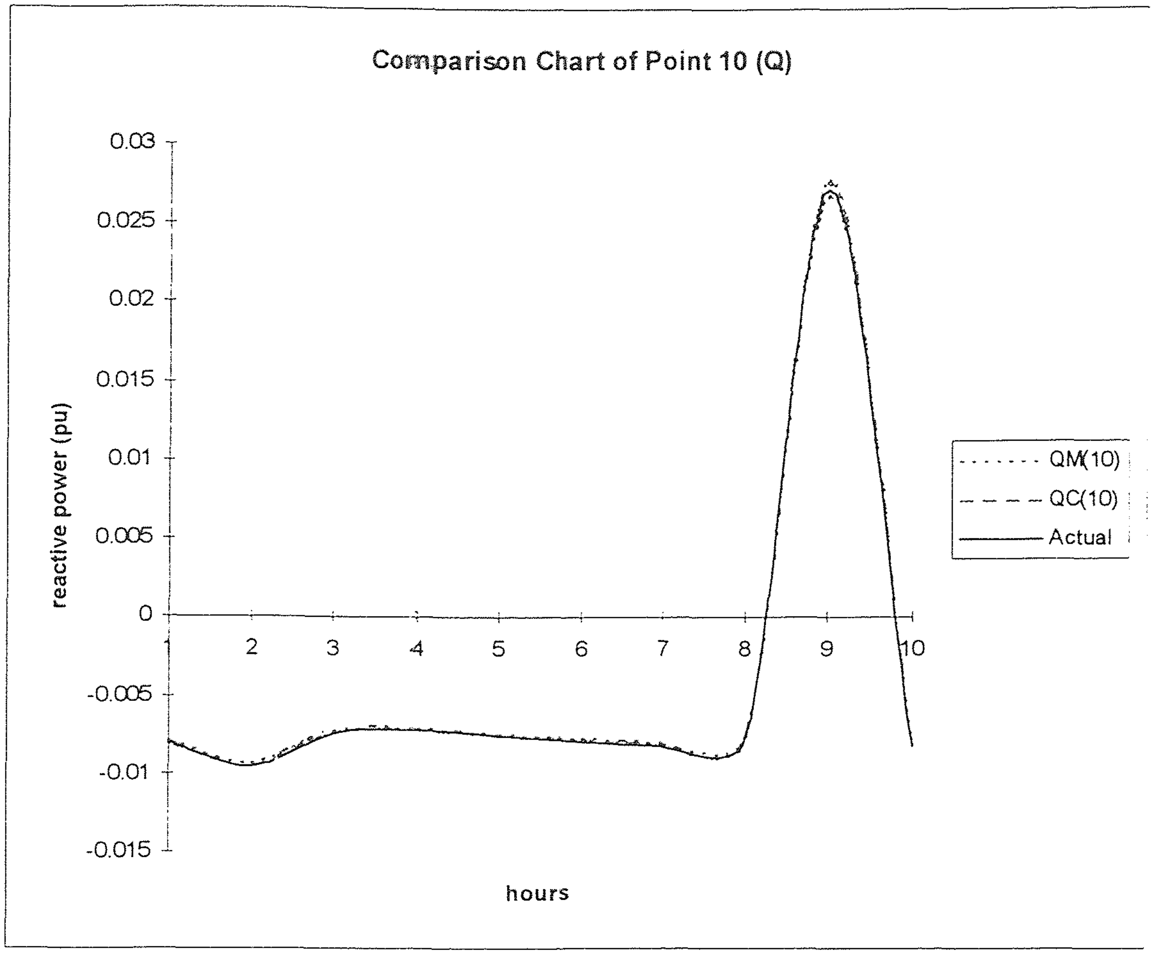


Figure 26 Comparison of Measured, Calibrated and Actual Q at Point 10

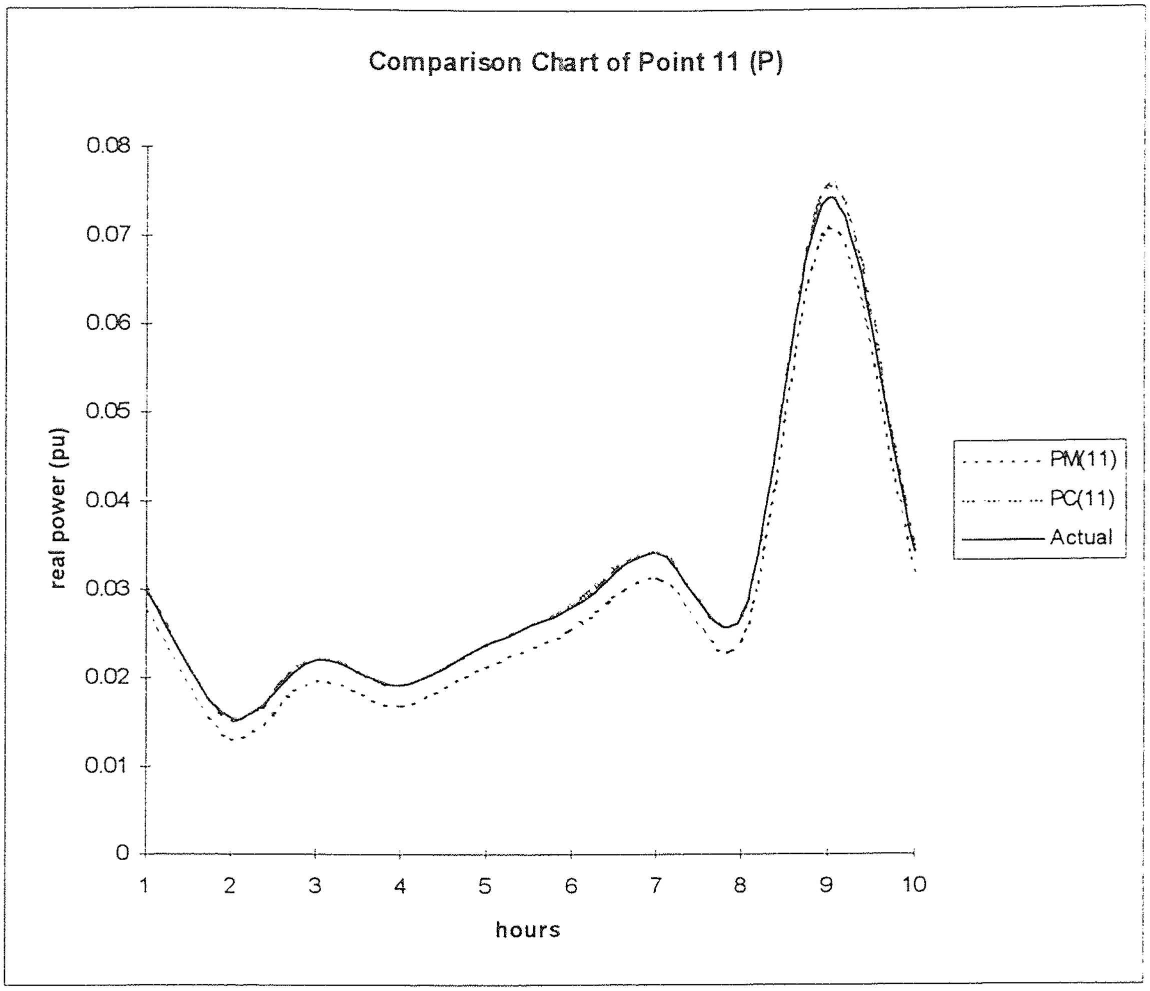


Table 27 Comparison of Measured, Calibrated and Actual P at Point 11

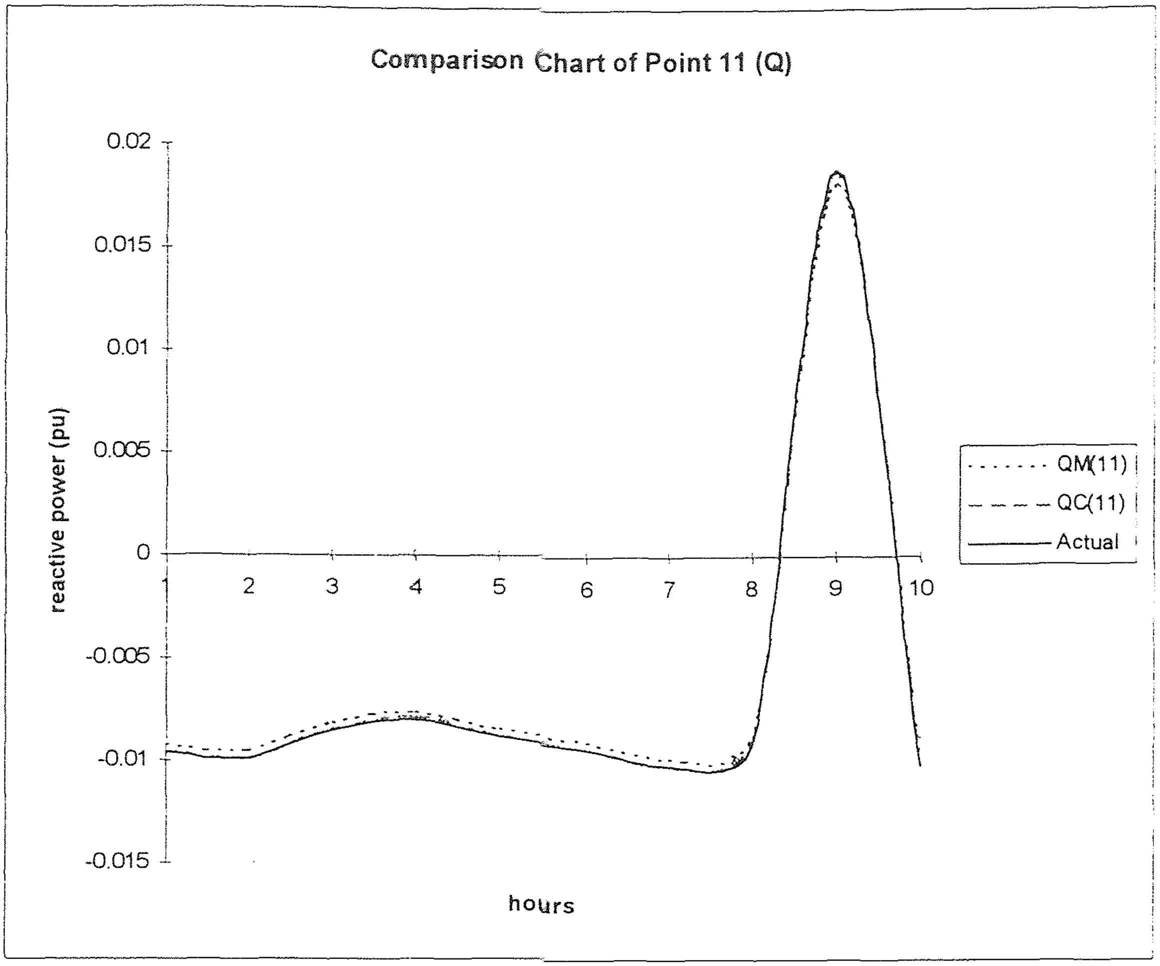


Figure 28 Comparison of Measured, Calibrated and Actual Q at Point 11

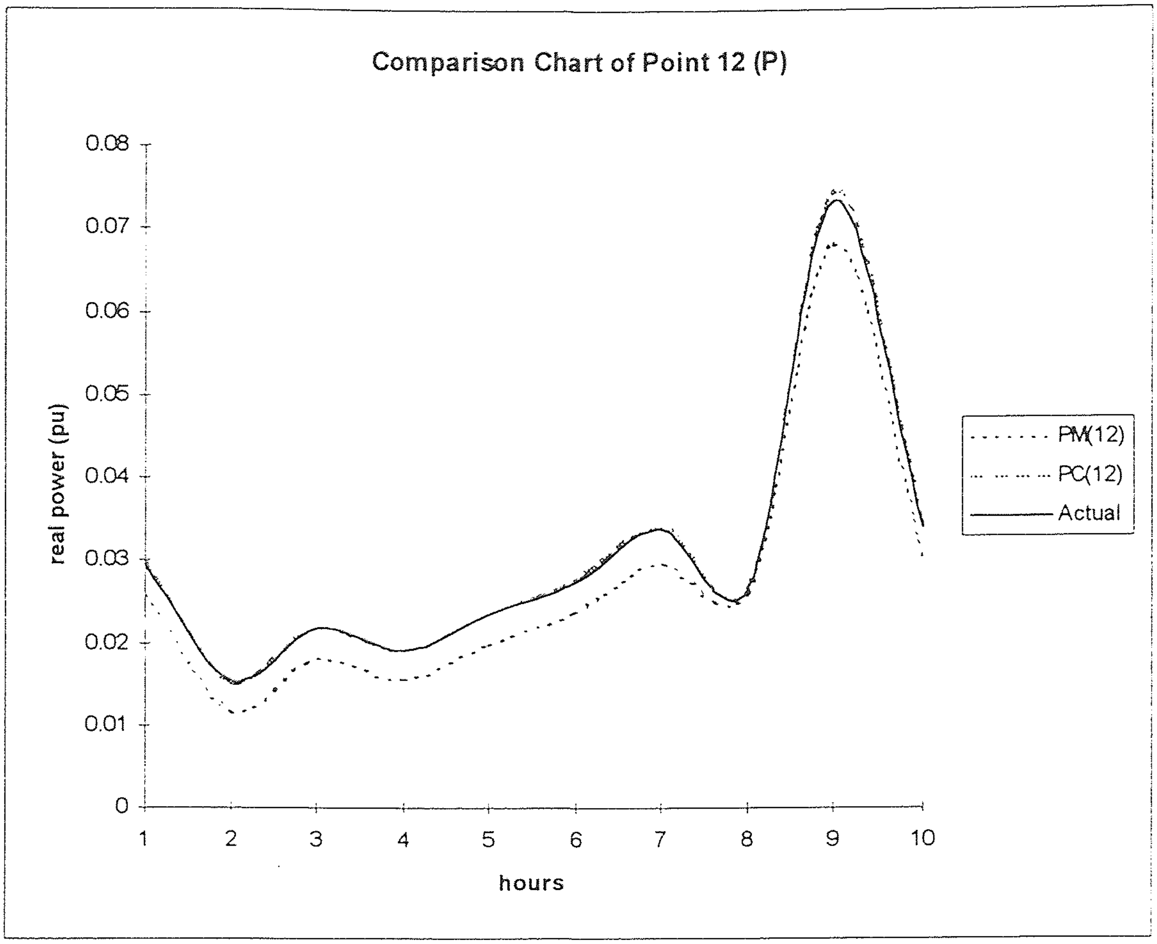


Figure 29 Comparison of Measured, Calibrated and Actual P at Point 12

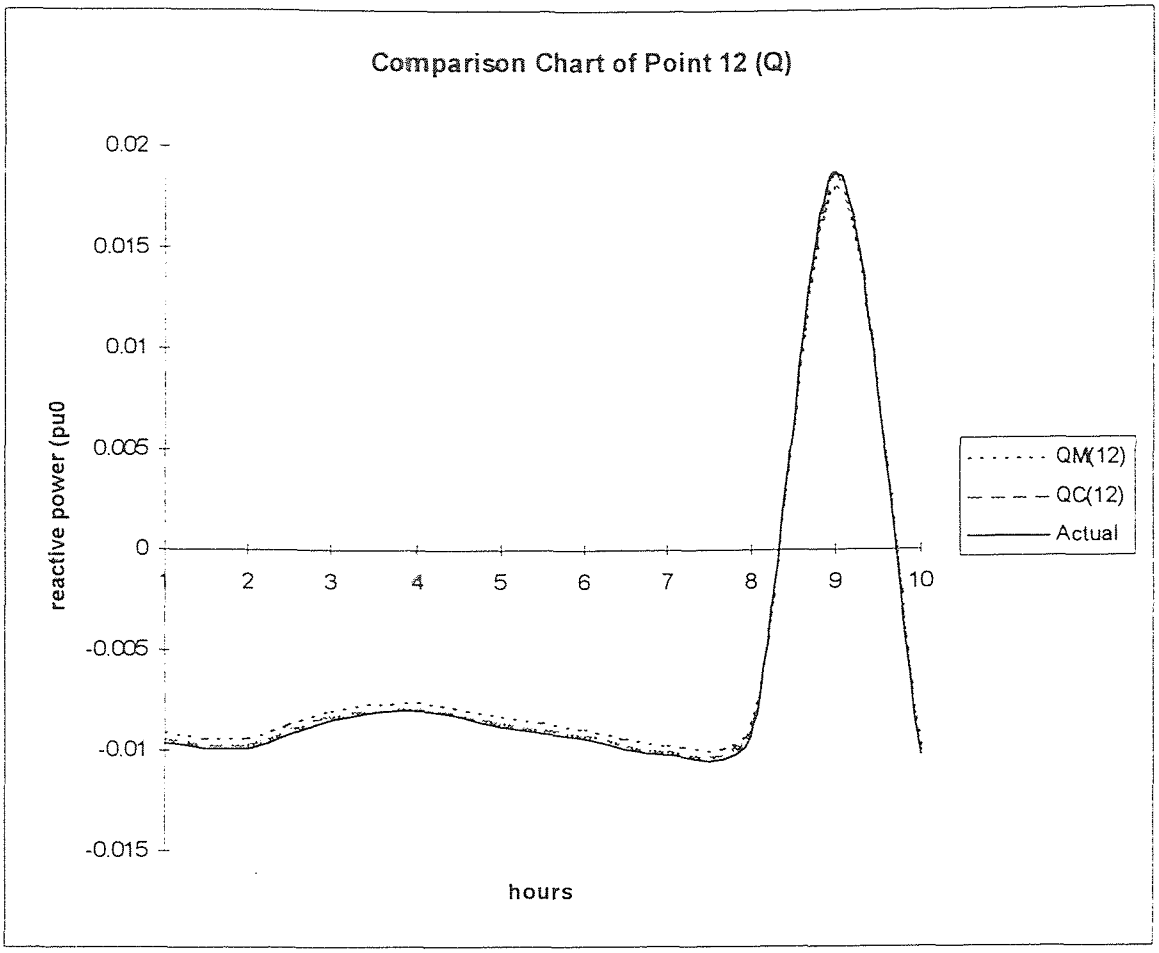


Figure 30 Comparison of Measured, Calibrated and Actual Q at Point 12

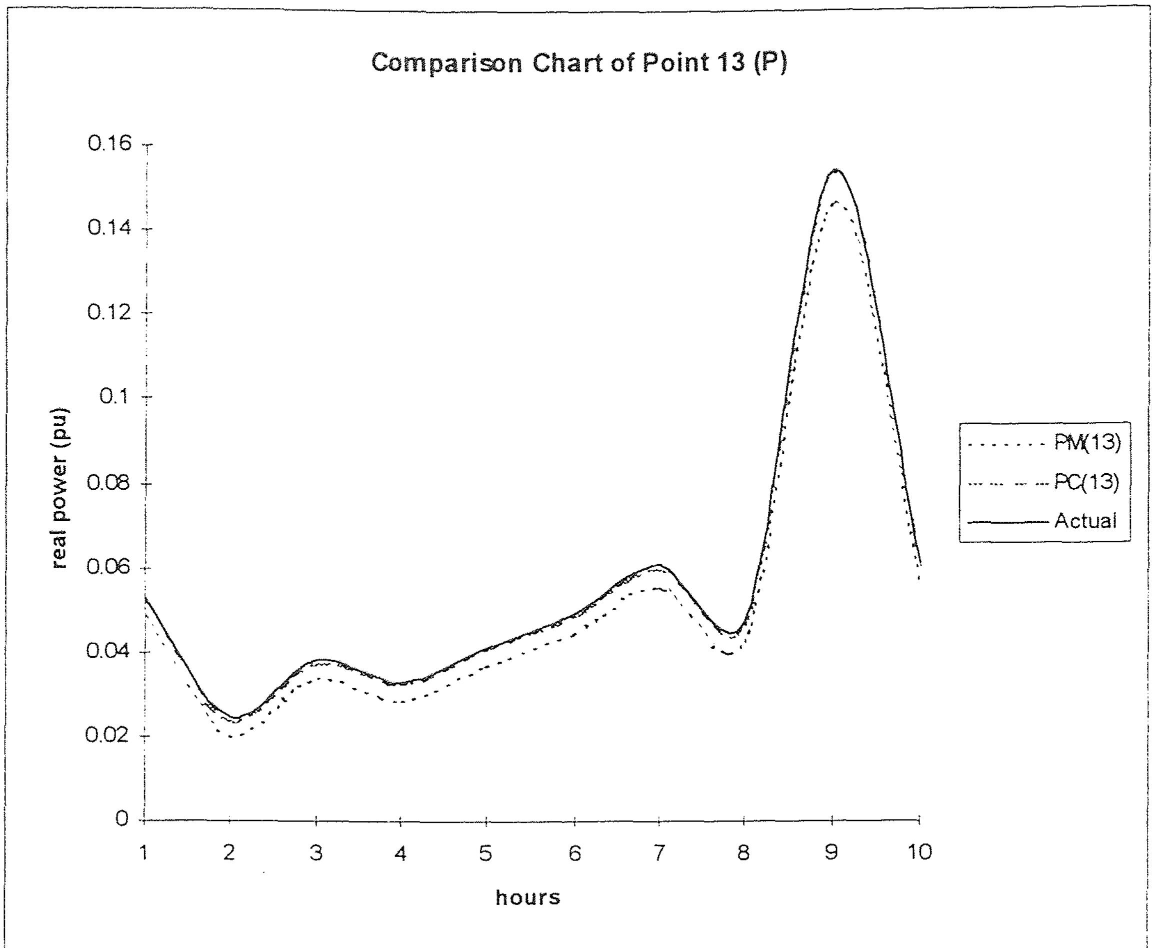


Figure 31 Comparison of Measured, Calibrated and Actual P at Point 13

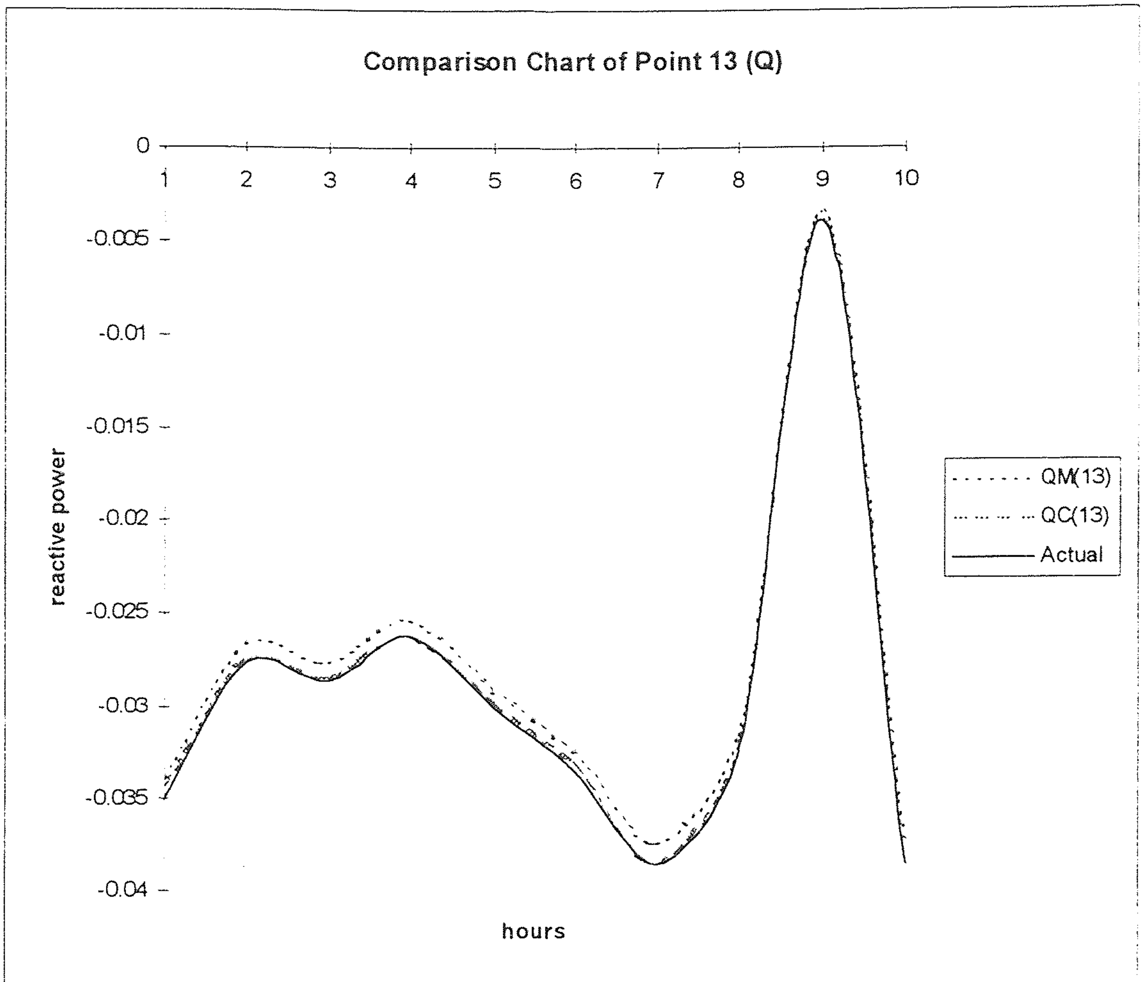


Figure 32 Comparison of Measured, Calibrated and Actual Q at Point 13

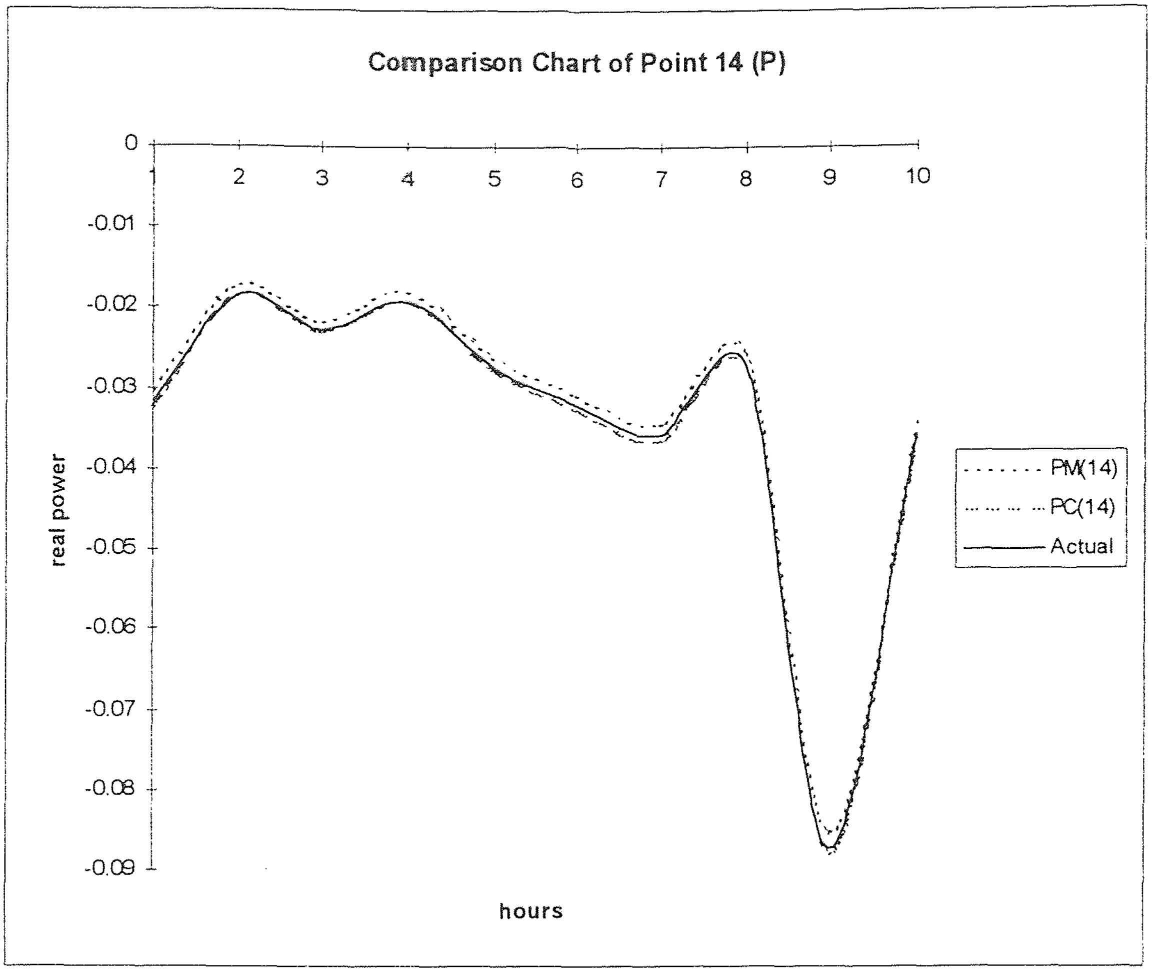


Figure 33 Comparison of Measured, Calibrated and Actual P at Point 14

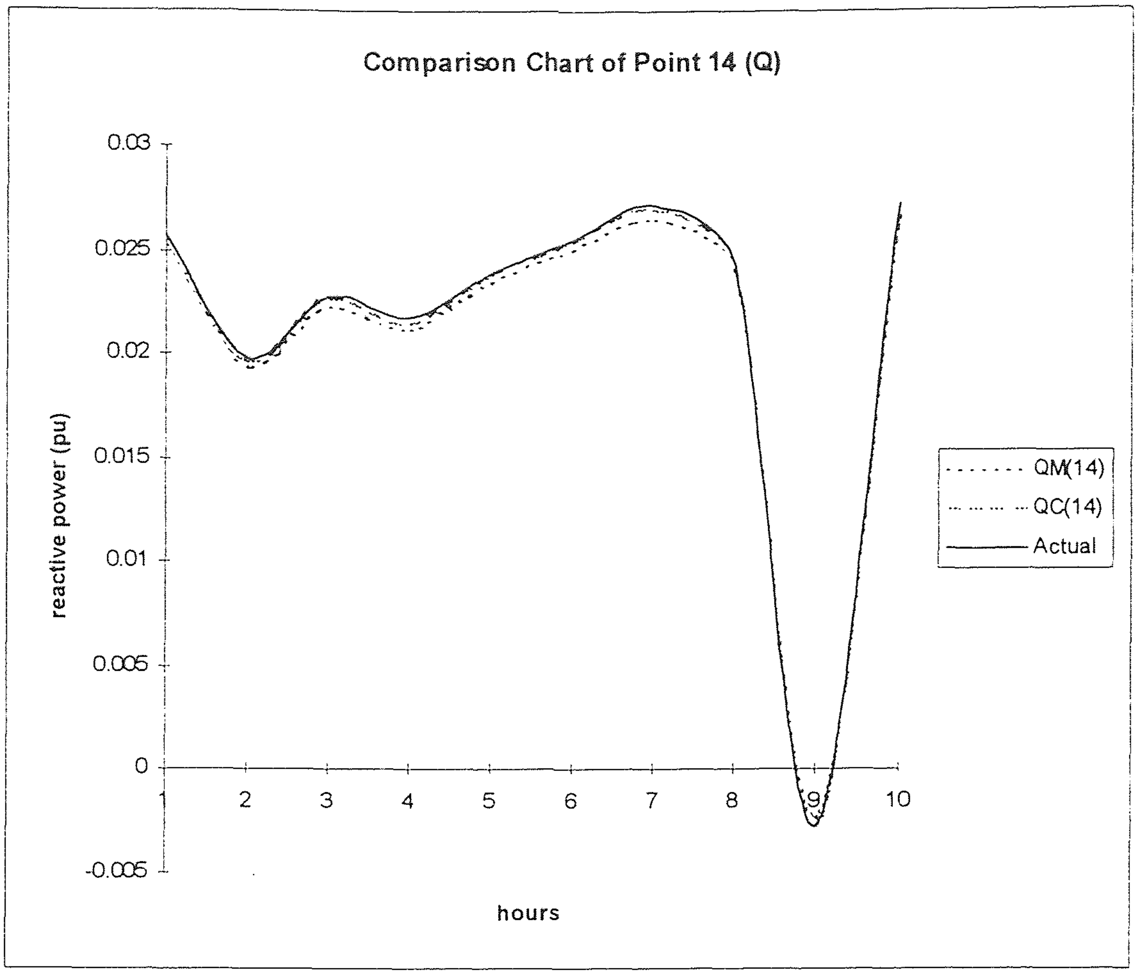


Figure 34 Comparison of Measured, Calibrated and Actual Q at Point 14

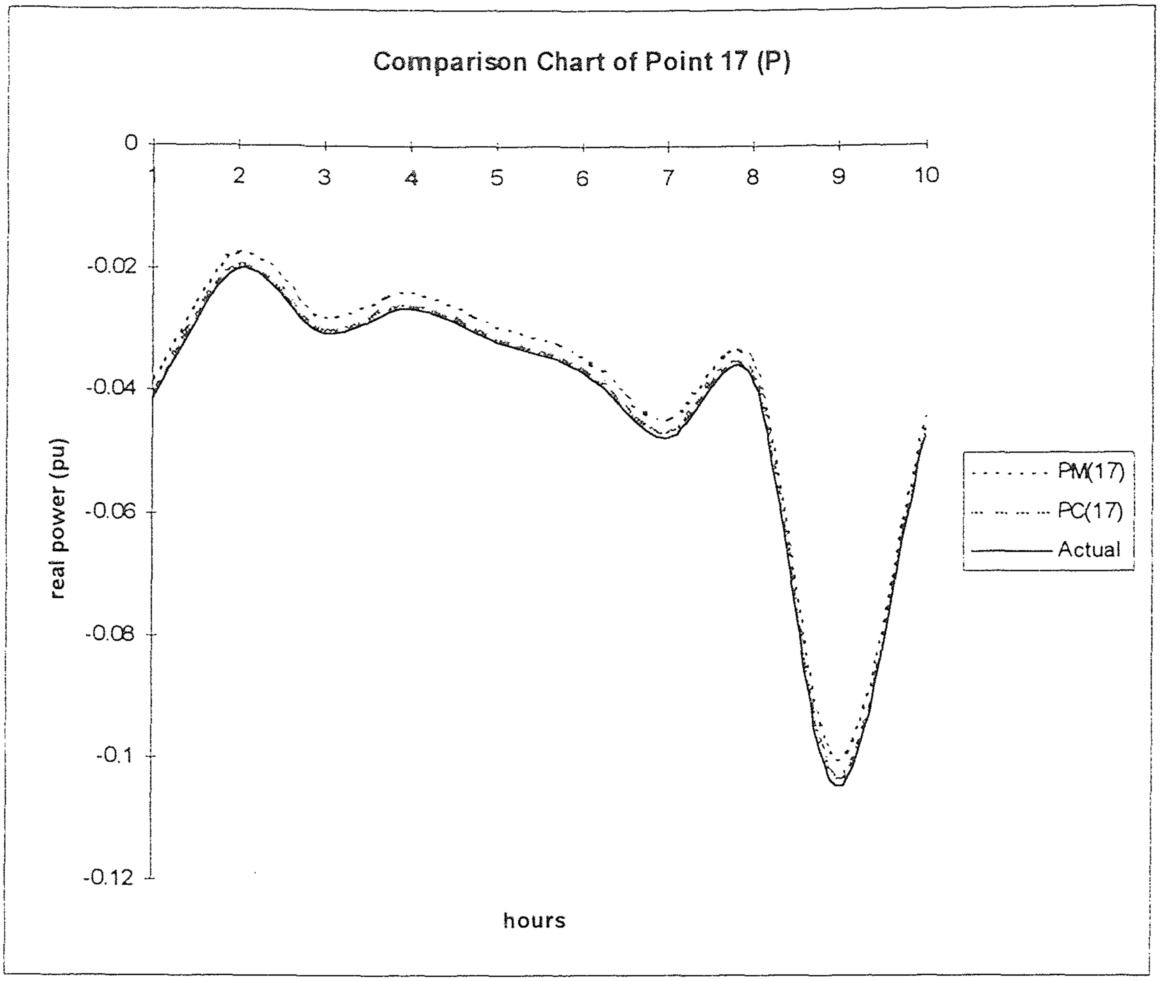


Figure 35 Comparison of Measured, Calibrated and Actual P at Point 17

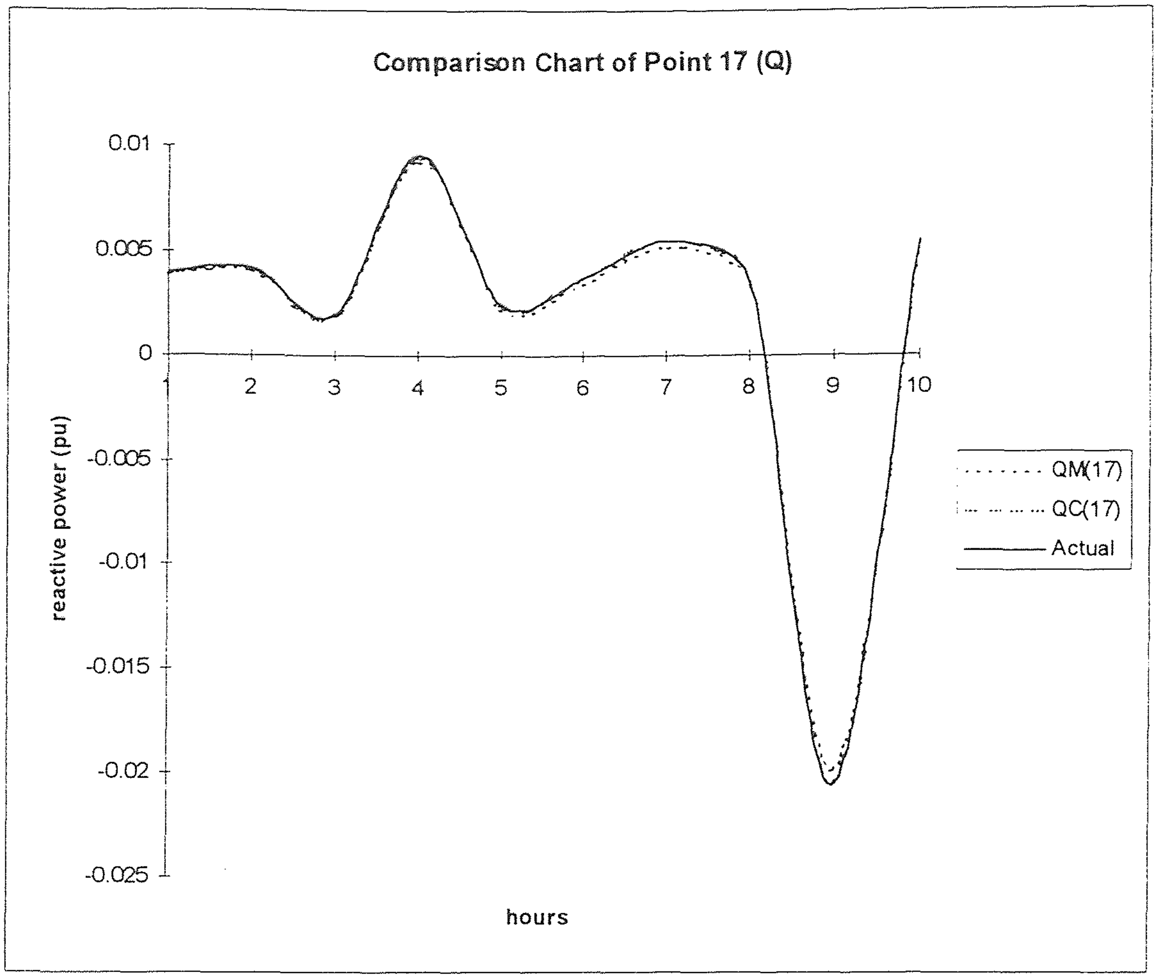


Figure 36 Comparison of Measured, Calibrated and Actual Q at Point 17

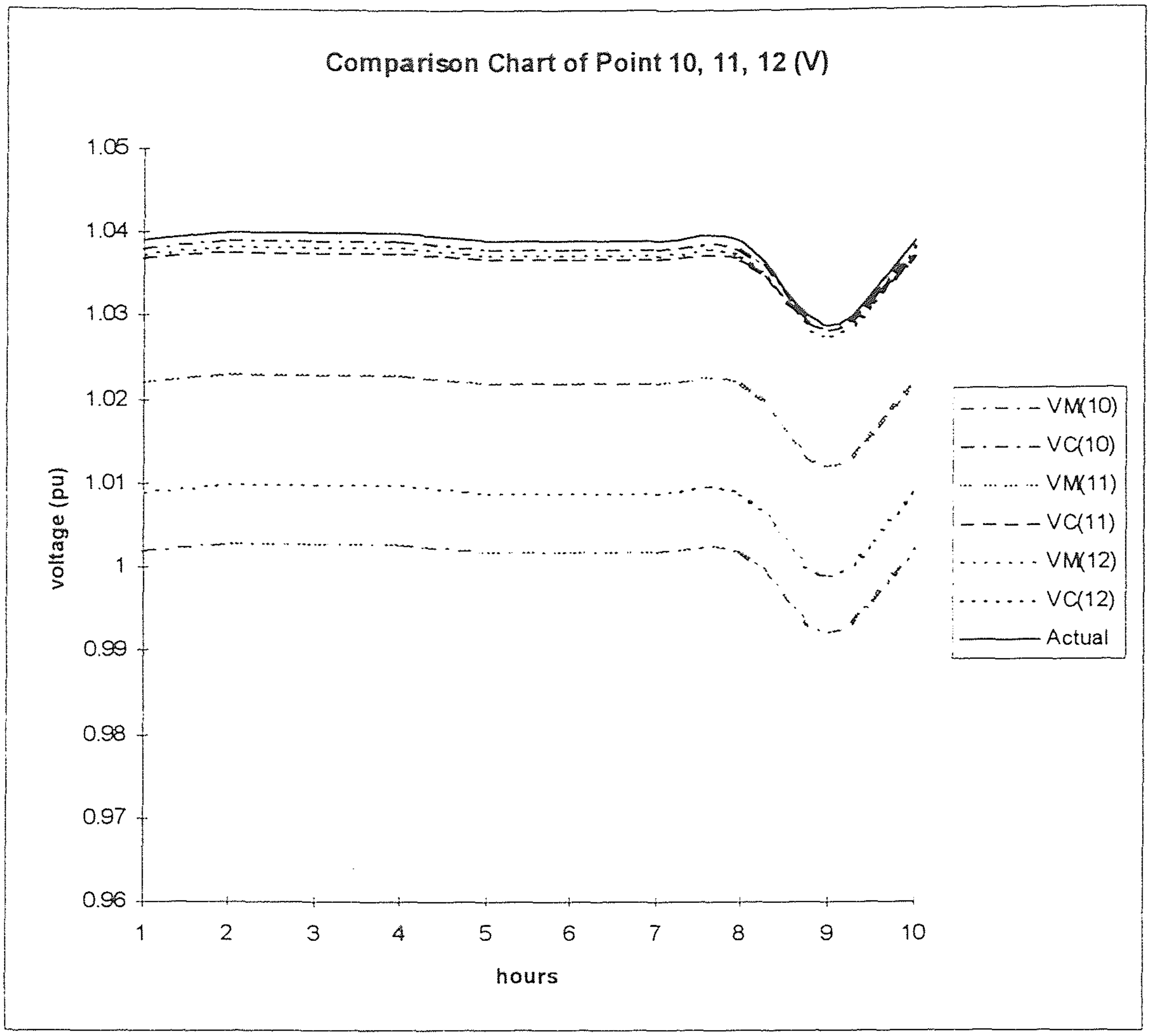


Figure 37 Comparison of Measured,Calibrated and Actual V of Point 10, 11, 12

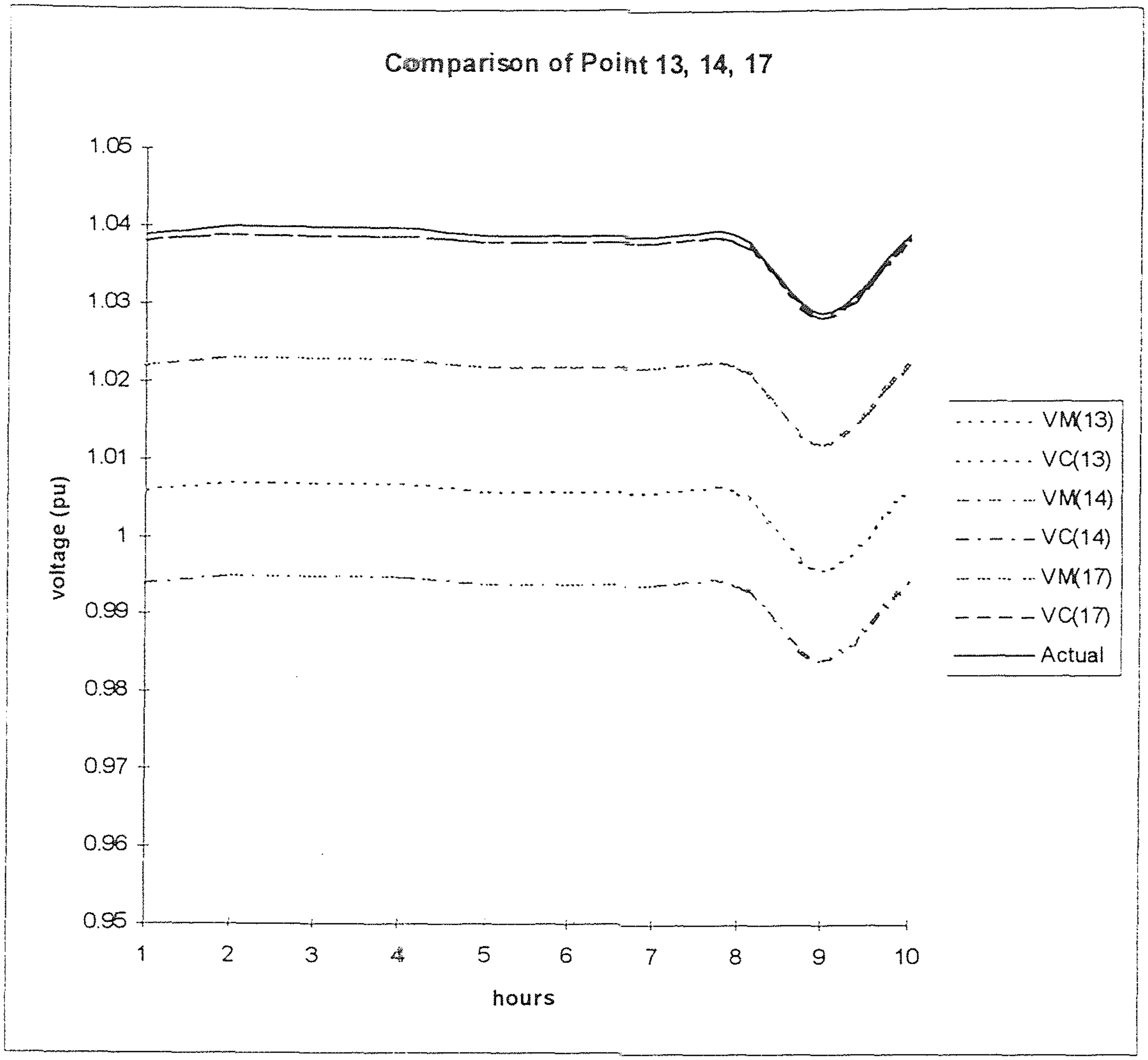


Figure 38 Comparison of Measured, Calibrated and Actual V of Point 13, 14, 17

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